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Finite Element Modeling of Mechanically Stabilized Earth Walls Built with Welded Wire Wall Panels

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FINITE ELEMENT MODELING OF MECHANICALLY STABILIZED EARTH WALLS BUILT WITH WELDED WIRE WALL PANELS

by

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(Under the Direction of Saman Hedjazi)

ABSTRACT

In this thesis, a finite element modeling of Mechanically Stabilized Earth (MSE) walls using welded wire wall panels was performed. The implementation of finite element modeling and analysis proved to be quite efficient in simulating the three-dimensional behavior of wall panels that are a part of MSE walls. The comprehensive finite element model included defined concrete and steel material properties in order to present both the realistic behaviors of each component in the model as well as better facilitating and increasing the accuracy of the simulation of numerous finite element analysis (FEA) cases. FEA was employed to simulate welded wire wall panels under the applied loads and to consider varying parameters of the model. The standard finite element tool (Abaqus) was used to conduct the analysis. Demonstrated behaviors and the model's performance were observed throughout the implementation of soil pressure and pullout loads on an anchorage system. The captured results were used to prove that the possibility of implementation of 3D panels as MSE wall facings, and to determine the mode of failure of panels, and to establish a sufficient anchorage system.

INDEX WORDS: ABAQUS, Mechanically stabilized earth walls, Welded wire panel, Finite element, Pullout test, Anchorage system.

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DEDICATION

To my mother and family.

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CHAPTER 1

INTRODUCTION

Background

A formal definition of a retaining wall would be a wall that serves the function of retaining soil by resisting the lateral forces generated and any surcharge loads associated with that particular fill (Walters, et al. 2016). Specifically, Mechanically Stabilized Earth (MSE) walls will be observed throughout this thesis in greater detail. Mechanically stabilized soil or Reinforced Earth is soil that is reinforced artificially in order to make the soil showcase better performance. Typically, Mechanically Stabilized Earth is used in conjunction with MSE walls in order to stabilize and retain soil for a variety of purposes. “Mechanically Stabilized Earth (MSE) walls are earth retaining structures that are constructed by placing alternating layers of reinforcement and compacted soil behind a facing element to form a composite material which acts integrally to restrain lateral forces” (Alzamora and Anderson 2009). During the selection process for the use of MSE walls one must consider numerous factors. For example, considerations should include geologic conditions, topographic conditions, environmental conditions, size of the structure, nature of the structure, aesthetics, durability considerations, performance criteria, availability of materials, experience with a particular system or application, and cost (Berg, Christopher and Samtani 2009). MSE walls should be capable of increased soil stability, the ability of long-term performance, protection from erosion, exhibit cost efficiency, employ effective usage of land, and display the suitability to have both permanent and temporary applications (Armtec 2016). MSE wall systems can be described through a variety of components. The wall system consists of the original ground, concrete leveling pad, wall facing panels, coping, soil reinforcement, select backfill and any loads and surcharges (Passe 2000).

Pertaining to the cost of implementing a MSE wall the typical cost of a precast MSE wall can be broken down as follows: The erection of panels and the profit contractors make throughout the process make up about 20-30 percent of total cost, reinforcing materials such as steel or polymers range from 15-30 percent of total cost, facing systems roughly amount to an estimated 20-40 percent of total cost, the wall fill including its placement being around 30-60 percent of total cost (Berg, Christopher and Samtani 2009). The facings of MSE walls can be considerably costly. The total construction cost is incurred by the facing due to its weight, which increases not only material costs but also those for time, labor and equipment. The weight of the facing is also the key point because there is the potential of instability and bearing failure. Therefore, the mission for this work is to provide a solution for this inefficiency in the application of MSE walls.

The welded wire panels also referred to as 3D panels are prefabricated panels that consist of a super-insulated core of rigid Expanded Polystyrene (EPS) sandwiched between two sheets of steel welded wire fabric mesh. Essentially galvanized steel truss wires pierce the polystyrene core at various offset angles in order to improve performance and are then welded to the sheets of steel Welded Wire Fabric Mesh (WWFM) on the outer layers of the panel. The truss behavior assists with the rigidity and shear elements for full composite behavior. 3D wire mesh panels serve many functions in construction for both internal and external applications for walls, floors, ceilings and roof structures in all types of construction. In its usage, 3D panels are placed into its intended position where layers of concrete or any other relevant material can be applied. These panels are effective in multiple capacities such as load carrying capacity, shear capacity and flexural capacity. Additionally, the implementation of rebar is applicable in these instances. Shear strength of the panels depends on the number of diagonals. All welded wire walls are also considered as being shear walls, and are considered efficient at transferring horizontal loads like wind and earthquake loads (Poluraju and Apparao 2015). Through research and experimentation, it has been found that 3D panels tested under lateral loads showed tremendous results for both post-cracking strength and ductile behavior (Poluraju and Apparao 2015).

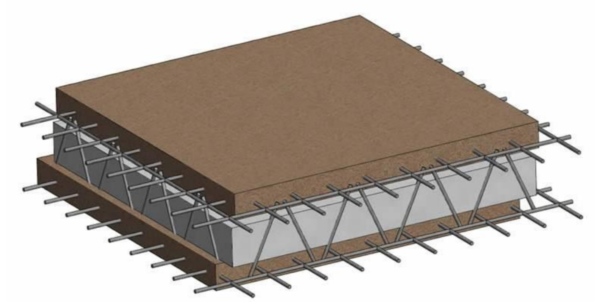


Figure 1: 3D Shotcrete Sandwich Wire Panels (Enzar Metal n.d.)

Research Objectives

The purpose of this investigation was to determine whether or not the implementation of 3D wire panels as a viable alternative for MSE wall facing is possible. In order to achieve this goal in this work the following was achieved.

1. Literature review to evaluate the results of previous finite element models of this type and other similar works.
2. Development of a three-dimensional finite element model of the 3D wire panel that is an accurate representation of real life conditions, characteristics, and behaviors.
3. Using the previously mentioned model to predict the behavior and response of the 3D wire panel under different circumstances.

Organization of Thesis

This thesis is organized into six chapters as follows:

- Chapter 1: Introduction - This chapter describes the objectives, scope, and thesis outline.
- Chapter 2: Literature Review and Background - This chapter provides a brief summary of previous research works related to MSE walls and 3D welded wire panels through literature review.

- Chapter 3: Numerical Analysis and Modeling - This chapter has the development of the FE model for the actual 3D welded wire panel is described, and the modeling results are presented. A means of verification for finite element analysis was detailed in this chapter. The comparison of finite element analysis and experimental results are presented.
- Chapter 4: Results and Discussion – The results of the pullout tests are presented and discussed in this chapter. Pressure, stress and deformation are presented in the results.
- Chapter 5: Findings and Recommendations – Using the results gathered in the previous chapter recommendations for selecting the best 3D wire panel for the specific conditions detailed in the thesis are made. The major findings of this work is made and explained.
- Chapter 6: Conclusion – This chapter presents the detailed summary as well as a main conclusion from this work and recommendations for future work.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

Mechanically Stabilized Earth Walls

MSE walls are alternatives for where reinforced concrete walls act as retaining walls and are used in order to retain soil as well as being suited for steep-sided terrain, soil subjected to slope instability, or in areas where foundation soils are poor. Similarly, to all walls in general MSE walls perform various functions and varies in regards to design and construction. Therefore, multiple agencies have established their own definitions and guidelines for MSE walls.

History of MSE Walls

Ever since ancient times, mankind has used different types of inclusions to improve the soil, for example the use of sticks to reinforce mud dwellings or straw to improve adobe bricks. However, it wasn't until the 20th century where the modern iterations of retaining wall construction were seen. Henri Vidal, a French architect and engineer, provided the research that lead to Reinforced Earth®. And not until the California State Highway 39 was built in 1972 was the technology first employed in the USA (Berg, Christopher and Samtani 2009). However, today MSE walls are a very popular choice in relevant situations and are extensively used. And of course there are many systems that can be implemented as well as the constant creation of new ones.

Varying components, engineering details, and varying system quality controls are all parameters to note with each system. Since there are so many MSE wall systems to consider the Highway Innovative Technology Evaluation Center (HITEC) was created to sort and evaluate MSE walls. In the modern era MSE walls have become common place and now every year in the United States it is estimated that 9,000,000 ft^2 of MSE retaining walls with precast facing are constructed (Berg, Christopher and Samtani 2009). Due to its extensive use MSE walls amount to about more than half of all transportation retaining walls also it is believed that every state within the US has constructed MSE walls.

MSE Wall Systems

MSE wall systems can be described through a variety of components. The wall system consists of the original ground, concrete leveling pad, wall facing panels, coping, soil reinforcement, select backfill and any loads and surcharges (Passe 2000). Potentially the most important of the wall's aspects are those that pertain to its reinforcement. Reinforcement geometry, material, and extensibility, which relates the reinforcement's deformation to the soil's deformation, are all concepts to be noted in preparation of a MSE walls reinforcement. The reinforced fill materials are also to be noted. Durability, good drainage, constructability, and good soil reinforcement interaction are all aspects that MSE walls require from wall fill. Ideally, well graded granular materials with high friction characteristics are required. Another consideration are the facings of MSE walls. There is an extensive number of facings that can be implemented in conjunction with MSE walls such as segmental precast concrete panels, dry cast modular block wall units, welded wire mesh, gabion facing (rock filled wire baskets), and geosynthetic facings (Berg, Christopher and Samtani 2009). Control the aesthetics of MSE wall with various options of color and finish as well as providing the necessary protection against erosion ad backfill sloughing. Also note that the facing used does indeed influence the settlement tolerances which are important.

Construction

The construction sequence may often be overlooked in terms of its contribution towards the behavior and performance of the Mechanically Stabilized Earth walls but it should not be ignored. For MSE walls with a precast panel facing the construction process begins with the preparation of the subgrade then proceeds to the placement of a leveling pad for the erection of the facing elements. An aspect that may seem underrated is the use of leveling pads. The leveling pad is not "structurally" important, however the leveling pad sets the horizontal and vertical alignment of the MSE wall. Next is the erection of the first row of facing panels on the prepared leveling pad.

Afterwards there is the placement and compaction of reinforced wall fill on the subgrade to the level of the first layer of reinforcement and its compaction as well as the placement of the first layer of reinforcing elements on the wall fill. The key to the performance of the MSE wall is the weight of the backfill on the soil reinforcement keeping the facing stabilized thanks to friction. Otherwise the facing would fail due to the backfill's tendency to push out (Kansas Department of Transportation 2008). After that there is the placement of the wall fill over the reinforcing elements to the level of the next reinforcement layer and compaction of the wall fill. And the process is repeated until completion for each sequential layer.

Advantages

Compared to technology that are similar in function that came before MSE walls there are several advantages it has. In comparison to conventional reinforced concrete and concrete gravity retaining walls, MSE walls have advantages in simple and rapid construction procedures and do not require as large of construction equipment. MSE walls also do not require special skills for construction. Also they require less site preparation than other alternatives as well as needing less space in front of the structure for construction operations. MSE walls do not need rigid, unyielding foundation support because MSE structures are tolerant to deformation. The walls are 25-50% cheaper than general concrete retaining walls and has the advantage of having the technical feasibility to achieve heights in excess of 100 ft. (30 m). Pre-manufacturing and quick construction is possible. For systems that are required to be 10 ft. or higher MSE walls are very practical because there is no need for special foundations (Berg, Christopher and Samtani 2009). Also MSE walls are comparatively more flexible. This flexibility allows for the capability to tolerate deformations and demonstrate higher resistance to seismic loading. In terms of customization MSE walls precast concrete facing elements can have varying textures and shapes not to mention any other aesthetic modifications.

Disadvantages

Note that the employment of Mechanically Stabilized Earth walls are accompanied with their imperfections. First wall geometries constructed at acute angles should be avoided because there can be complications in reinforcement as well as interference from obstructions like piles and/or drainage structures. Second these same wall obstructions have to be avoided by any reinforcement support through skewing or cutting which in turn leads to impact on internal stability of the wall. An example of a construction issue would include the improper placement and compaction of backfill which directly impacts the facing of a MSE wall (i.e. bulging) (Alzamora and Anderson 2009). Other disadvantages of MSE walls include the fact that they require a relatively large space (e.g., excavation if in a cut) behind the wall or slope face to install required reinforcement. Also the walls require the use of select granular fill which at some sites, the cost of importing suitable fill material may render the system uneconomical. Another disadvantage is that the design of soil-reinforced systems often requires a shared design responsibility between material suppliers and owners. Projects involving MSE walls can often times have a disconnect between the overall project civil and structural design engineer and geotechnical engineer, and the MSE wall design engineer because each are trying to achieve their own agenda are trying to have the MSE wall fulfill their criteria within their respective fields (Harpstead, Schmidt and Christopher 2010). Other typical problems one may encounter when interacting with MSE walls are related to aspects such as geometry, wall layout, obstructions, wall embedment, surface drainage, contractor experience, claims, backfill placement soil compaction, panel joints, leveling pad, and the durability of the facing (Alzamora and Anderson 2009). The total construction cost is incurred by the facing due to its weight, which increases not only material costs but also those for time, labor and equipment. The weight of the facing is also key because there is the potential of instability and bearing failure. Fortunately, the mission for this work is to provide a solution for this inefficiency in the application of MSE walls.

3D Wire Panels

Potentially this work can produce the solution of introducing an innovative concept in the design and manufacturing for the MSE wall facing that will use 3D shotcrete sandwich wire panels to counteract the issue posed by the weight of the facing with a less heavy option, thus leading to the substantial reduction of the material, construction labor, transportation, equipment costs, and time involved. Also the hope is that eventually the 3D wire panels can provide the possibility of enabling the use of MSE walls to sites with softer ground. 3D wire panels can serve as a direct replacement for concrete walls, masonry walls, or any other rigid material wall. The design of the 3D panel can be drawn by an architect in a drawing that satisfies the necessary engineering requirements or can easily be completed using the assistance of a multitude of software.

3D wire panels also referred to as 3D panels are prefabricated panels that consist of a super-insulated core of rigid Expanded Polystyrene (EPS) sandwiched between two sheets of steel welded wire fabric mesh. Essentially galvanized steel truss wires pierce the polystyrene core at various offset angles in order to improve performance and are then welded to the sheets of steel Welded Wire Fabric Mesh (WWFM) on the outer layers of the panel. The truss behavior assists with the rigidity and shear elements for full composite behavior. 3D wire mesh panels serve many functions in construction for both internal and external applications for walls, floors, ceilings and roof structures in all types of construction. In its usage, 3D panels are placed into its intended position where layers of concrete or any other relevant material can be applied. 3D panels are effective in load carrying capacity, shear capacity and flexural capacity (Poluraju and Apparao 2015).

The way that 3D panels need to be connected is an important aspect that is not to be ignored. Typical 3D panels have shear connectors. Under lateral loading the strength of panels are found to be suitable for safety and eco-friendly building construction. When erecting the panels, the first two panels are placed where they can form a corner and the adjacent panels are bonded together (Poluraju and Apparao 2015). The joining mesh needs to bind to the bounds with the appropriate spacing given the applicable needs. Panels at the corners shall be joined corner joining mesh (Building Materials & Technology Promotion Council Ministry of Housing & Urban Poverty Alleviation 2015). After the panels are firmly attached, the panel tops can be brought on-line using the appropriate bracing based on expected conditions. Note that all bracing should be located on the same side of the wall, opposite the side which will receive concrete first (Poluraju and Apparao 2015).

All concreting work shall be done in accordance with the proper and appropriate guidelines. A possible method for the application of concrete is that the concrete is sprayed on the walls as shotcrete. Proper design is essential for specifying details in terms of concrete implementation. Factors such as strength and mix design as required by the structural engineering design. For layering of the concrete or shotcrete a layer needs to be applied to a thickness that encases the welded-wire fabric and an additional layer to achieve the final thickness is required (Building Materials & Technology Promotion Council Ministry of Housing & Urban Poverty Alleviation 2015). Note that the curing and cleaning of the concrete surface should be in accordance to general concrete practices. It has been observed that the axial compression strength of a typical 3D wire panel depends on compressive strength of concrete used in association and the aspect ratio of the panel (Poluraju and Apparao 2015). Strengthening the panel is also possible. Through the sacrifice of weight reduction and the partial removal of the polystyrene portion of the panel in order to fill in with some concrete. Additionally, the implementation of rebar is applicable in these instances. Shear strength of 3D panels depends on the number of diagonals (Poluraju and Apparao 2015). All 3D walls are also considered as being shear walls, and are considered efficient at transferring horizontal loads like wind and earthquake loads (Poluraju and Apparao 2015). Through research and experimentation, it has been found that 3D panels tested under lateral loads showed tremendous results for both post-cracking strength and ductile behavior (Poluraju and Apparao 2015).

Therefore, due to the information stated through research, the implementation of 3D wire panels as a viable alternative for MSE wall facing is possible. Going forward in this work through the efforts of additional review and finite element analysis the advantages of 3D panel use will be fully displayed. If the weight of the MSE wall facing can be reduced because of the use of 3D shotcrete sandwich wire panels as well as displaying characteristics that prove it to be a viable MSE alternative, then there will be substantial savings in the construction, equipment, labor, material, and transportation costs as well as the increase in the stability and performance.

Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes

This set of guidelines was created by the Federal Highway Association (FHWA) in order to help engineers identify and evaluate MSE wall applications as well as Reinforced Soil Slopes (RSS). With the guidelines as a reference engineers have the ability to select, design, specify, monitor and contract for the construction of MSE walls. Over the last 35 years the development and use of MSE walls is something that engineers have encouraged Based upon Load and Resistance Factor Design (LRFD) for MSE wall structures.

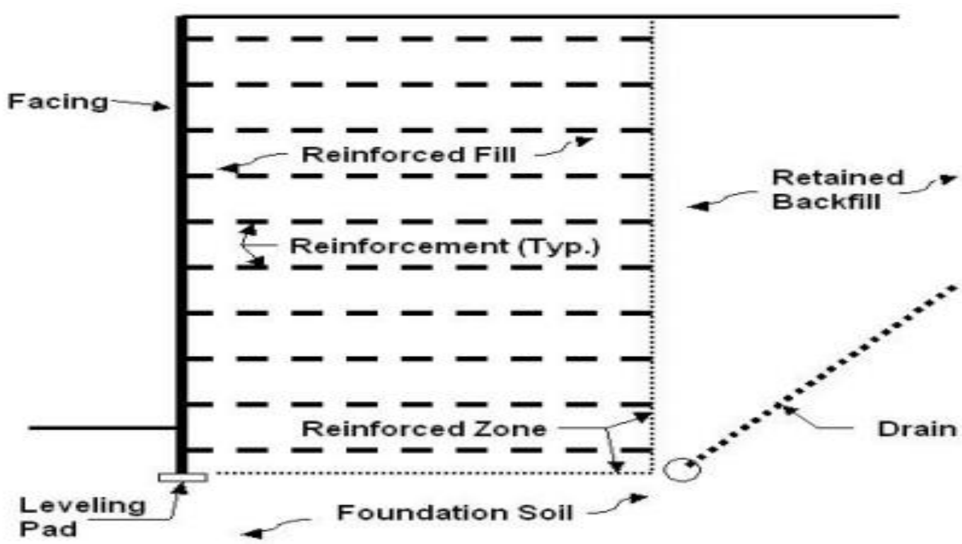


Figure 2: Simple cross section of an MSE structure (Berg, Christopher and Samtani 2009)

Compared to technology that are similar in function that came before MSE walls there are several advantages it has. There is the elimination of costs for foundation improvements that may be necessary for support. Temporary MSE wall structures are cost effective as opposed to other methods in cases involving temporary detours, embankments, abutments, and phased construction (Berg, Christopher and Samtani 2009).

In comparison to conventional reinforced concrete and concrete gravity retaining walls, MSE walls have these advantages (Berg, Christopher and Samtani 2009):

- Use simple and rapid construction procedures and do not require as large of construction equipment.
- Do not require special skills for construction.
- Require less site preparation than other alternatives.
- Need less space in front of the structure for construction operations.
- Reduce right-of-way acquisition.
- Do not need rigid, unyielding foundation support because MSE structures are tolerant to deformations.
- Are cost effective. (25-50% cheaper than concrete retaining walls)
- Are technically feasible to heights in excess of 100 ft. (30 m).

Also MSE walls are comparatively more flexible. This flexibility allows for the capability to tolerate deformations and demonstrate higher resistance to seismic loading (Berg, Christopher and Samtani 2009). In terms of customization MSE walls precast concrete facing elements can have varying textures and shapes not to mention any other aesthetic modifications. Fortunately, these guidelines provided by the FHWA establish a general outline of MSE wall perimeters and construction practices that help showcase an adequate background of MSE walls.

Mechanically Stabilized Earth Wall Inspector's Handbook

Any of these aforementioned aspects of are all key for the performance and function of a MSE wall. The preparation of the foundation for MSE walls is essential as well. The foundation for the structure shall be graded level for a width equal to or exceeding the length of soil reinforcement or as shown in the plans. Prior to beginning fill placement, the area under the MSE wall footprint should be prepared and compacted with a minimum of five passes with an appropriate vibratory roller weighing at least eight tons. An aspect that may seem underrated is the use of leveling pads (Passe 2000). The leveling pad is not "structurally" important, however the leveling pad sets the horizontal and vertical alignment of the MSE wall. It is important that the wall is level, otherwise the panels will bind against each other causing spalling of the edges and corners which is detrimental (Passe 2000). In terms of this project all considerations for MSE wall facings have to employ a positive relationship with the foundation and leveling pad of the retaining wall.

Armtec Mechanically Stabilized Earth (MSE) Wall Systems

Armtec is an infrastructure and construction materials company based in Canada that has provided an informative product guide for their version of MSE walls. Essentially this guide showcases data and knowledge pertaining to how MSE wall creators expect their product to perform as well as their capabilities. Armtec also provides multiple examples of the different types of potential MSE walls for consideration. Specifically, rock faced welded wire mesh walls and vegetated welded wire mesh walls are two cases related to this research. Rock faced welded wire mesh uses the combination of a welded wire mesh facing, biaxial grid wrap, uniaxial geogrid soil reinforcement, and a rock aggregate facing that is best suited for structures with geometries that are steep (Armtec 2016). Vegetated welded wire mesh walls uses the combination of welded wire mesh facing, biaxial green grid wrap and uniaxial geogrid for soil reinforcement. Note that during the construction of a vegetated welded wire mesh that seeded topsoil or hydro-seed material is placed behind the biaxial green grid at the face of the wall to initiate vegetation growth that leads to a product that is both environmentally friendly and can provide an aesthetically pleasing structure (Armtec 2016). The numerous considerations for the types of facing for MSE walls lead to a plethora of possibilities for potential designs and components. Due to this fact the proper solution to the main issue at hand can be created and implemented.

Kansas Department of Transportation (KDOT)

As a component of their bridge construction manual the Kansas Department of Transportation specifically highlighted mechanically stabilized earth walls. Essentially the Kansas DOT provides guidelines for inspectors and presents various features that are similar to others. According to KDOT the key to the performance of the MSE wall is the weight of the backfill on the soil reinforcement keeping the facing stabilized thanks to friction. Additionally, KDOT provides information about the panels on facings for MSE walls. In terms of reinforcement connections on panels it should be noted that panels towards the bottom of the wall will typically have more connections than compared to the top (Kansas Department of Transportation 2008). The facing panels of a MSE wall has to be placed spaced particularly well or else eventually issues involving cracking and spalling will become apparent. Other factors such as alignment, grade, and leveling are important for the facing of MSE walls. As mentioned by the KDOT the facings employed by MSE wall projects need to deliver the appropriate performance and behavior when subjected to the backfill's tendency to push out. Therefore, any potential alternative suggested to be implemented as a MSE wall facing need to prove its capabilities in this regard.

Review of Mechanically Stabilized Earth Wall Performance Issues

Generally, MSE walls do not fail completely however it is essential that their performance be analyzed and reviewed. There are multiple transportation departments across the country that take matters into their own hands and have developed or are in the process of developing systems to be implemented for the design and construction process of MSE walls. All of this effort is for the purpose of generally improving MSE walls. Typical problems one may encounter when interacting with MSE walls are related to geometry and wall layout, obstructions, wall embedment, surface drainage, contractor experience, claims, backfill placement and compaction, panel joints, leveling pad, durability of facing (Alzamora and Anderson 2009). Some examples of design issues are as follows. First wall geometries constructed at acute angles should be avoided because there can be complications in reinforcement as well as interference from obstructions like piles and/or drainage structures. Second these same wall obstructions have to be avoided. Skewing or cutting leads to an impact on internal stability of the wall. An example of a construction issue would include the improper placement and compaction of backfill which directly impacts the facing of a MSE wall (i.e. bulging). It should be noted that the construction process can be key in affecting the performance of MSE walls. Any facing implemented in a MSE wall needs to be able to withstand construction errors that can be a detriment to the retaining wall.

Feasibility of a Management System for Retaining Walls and Sound Barriers

Systems for wall/ barrier management can easily be put into place because these systems often share similarities to bridge management systems. Inventory, inspection, condition assessment, maintenance, performance evaluation, and asset valuation are all components that are apart of wall management (Hearn 2003). Wall management is essential because it is entirely possible that failures in walls can averted more easily. In the case of this work the management of the facings of MSE walls needs to be a consideration. Specifically, in this work condition assessment and performance evaluation are both aspects that play a role in the implementation of facings. The performance under varying conditions are observed extensively throughout this project.

Sustainable Geotechnical Asset Management along the Transportation Infrastructure Environment Using Remote Sensing

Often times the geotechnical aspects of walls are overlooked or ignored when it comes to an asset management system. Knowing the displacement or deformation is highly valuable for predicting conditions both externally and internally. Entities and reasons such as the difficulty in establishing potential long-term expectations on the performance and overall life-cycle behavior of a retaining wall as well as the fact that monitoring the health of a geotechnical asset may require expensive and time-consuming methodologies are all important when thinking about the geotechnical aspects of wall management (Wolf, et al. 2015). Geotechnical aspects of MSE walls cannot be overlooked and are essential for the consideration of alternate wall facings like the 3D wire panel.

Quik Build Panels

3D wire panels can serve as a direct replacement for concrete walls, masonry walls, or any other rigid material wall. The design of the 3D panel can be drawn by an architect in a drawing that satisfies the necessary engineering requirements or can easily be completed using the assistance of a multitude of software. The way that 3D panels need to be connected is an important aspect not to be ignored. Connections from panel to panel should be joined with a joining mesh (Building Materials & Technology Promotion Council Ministry of Housing & Urban Poverty Alleviation 2015). The joining mesh needs to bind to the bounds with the appropriate spacing given the applicable needs. Panels at the corners shall be joined corner joining mesh (Building Materials & Technology Promotion Council Ministry of Housing & Urban Poverty Alleviation 2015). The mesh shall be placed over the joint at the corner and shall be bounded with a binding wire to the panels (Building Materials & Technology Promotion Council Ministry of Housing & Urban Poverty Alleviation 2015). Binding should be done either by a binding wire or a tool with a similar and capable function.

All concreting work shall be done in accordance with the proper and appropriate guidelines. A possible method for the application of concrete is that the concrete is sprayed on the walls as shotcrete. Proper design is essential for specifying details in terms of concrete implementation. Factors such as strength and mix design as required by the structural engineering design. For layering of the concrete or shotcrete a layer needs to be applied to a thickness that encases the welded-wire fabric and an additional layer to achieve the final thickness is required (Building Materials & Technology Promotion Council Ministry of Housing & Urban Poverty Alleviation 2015). Note that the curing and cleaning of the concrete surface should be in accordance to general concrete practices. The composition of the materials used as well as the nature of their bonding are all significant to the 3D wire panel. The material and bonding aspects of panels has the potential to affect the characteristics in both positive and negative ways.

CHAPTER 3

NUMERICAL ANALYSIS AND MODLEING

Abaqus

Problem solving is an essential tool for engineers. For engineers it is important to solve these problems through a variety of different methods. One example of such methods is the use of finite element analysis (FEA). Essentially FEA employs numerical equations to find and predict the behavior of any particular entity under real world conditions. In order to simplify this process engineers, search for powerful and productive tools that can provide solutions to their needs. So in an effort to complete tasks using finite element analysis engineers use computer based software to gain solutions.

One such example of a tool that can be used to perform finite element analysis is the software known as Abaqus. Abaqus allows for a powerful modeling approach that allows users the ability to work with geometry based data as well as giving users advanced customization capabilities and user-defined inputs giving individuals a chance to fulfill their simulations as realistic as possible. Abaqus also boasts massive range of analysis functionality, such as acoustics, connectors, damage, fracture, and failure. Some of the software's applications can include and are not limited to full vehicle loads, dynamic vibration, multibody systems, impact/crash, nonlinear static, thermal coupling, and acoustic-structural coupling (Dassault Systemes 2013). Some of Abaqus's most important capabilities are its ability to create parts and assemblies through sketches as well having the ability to have geometries imported from other software. Additionally, not only does Abaqus mesh models but it also provides several approaches to creating simple and complicated meshes. It is also possible to remesh in order to provide more accurate results. It should be noted that contact modeling is possible and the ability to model interactions between deformable bodies, rigid bodies, and self-contact are also possible. Another key feature is that Abaqus can also automatically detect contact.

Advanced analysis is a major component of the Abaqus software that gives users the opportunity to perform a plethora of various tasks. Of course linear and nonlinear analysis is apart of Abaqus's capabilities. The implicit solution technology in Abaqus can be key solving static and low speed dynamic events like sealing pressure or crack propagation. The explicit solution technology is well suited for high speed dynamic events like drop testing, crashworthiness, and ballistic impact. Additionally, general linear analyses can be performed in cases where the linear response can depend on prior nonlinear history. Fortunately thanks to this powerful tool being available the numerical analysis can be conducted quickly and efficiently.

Verification

In an effort to validate this work going forward it's apparent that some verification is necessary to showcase that the methodology used for analysis is worthy to be considered. In the pursuit of obtaining verification of the pullout method employed in this thesis, research was conducted in order to find examples of pullout tests done by other relevant entities. Finding the appropriate example is essential in order to provide a basis for the analysis done in this project. Therefore, in an effort to determine what a suitable example for this project was, certain criteria had to be fulfilled. First of all, the pullout test had to be performed by a scholarly and trustworthy source. Secondly both inputs and outputs of the experiment had to be provided as well as proving to be reproduced for this work. Meaning that the researchers detail adequate amounts of information so that a duplicate can be created and used for verification for this project. Fortunately, a relevant example was found within the thesis created by Xin Li titled, "Finite Element Modeling of Skewed Reinforced Concrete Bridges and the Bond-Slip Relationship between Concrete and Reinforcement", which was submitted to Auburn University. Using their example of a pullout test and the information provided as a base the methodology to performing a pullout test can be practiced and verified in order to help advance this project forward. The success of performing this task provides a substantial benefit to streamlining the completion of any other potential pullout analysis because if the verification of performing the pullout test is completed successfully once then all that is needed is following a similar procedure on the actual model. It is important to note that this verification does not affect the results and conclusions made in this thesis. This verification is a method to ensure and verify that the inputs for parameters such as geometry, material properties, boundary conditions, loads, element type selection, and element size are done correctly by the user. It is essential that Abaqus is properly implemented in the finite element process by the user. Thus, the sections in this thesis about the verification builds trust that the user is properly employing the correct procedures in Abaqus and the results displayed later in this thesis can be trusted.

Research Verification

Fortunately, the research created by Xin Li titled, "Finite Element Modeling of Skewed Reinforced Concrete Bridges and the Bond-Slip Relationship between Concrete and Reinforcement", can function as a guide for verification. The documentation of their research is suitable for this project's numerical analysis verification. Using the information provided there can be a determination of the process that needs to be employed. Important parameters such as model dimensions, material properties, boundary conditions, etc. are all key.

Verification Model

Employing the data in the aforementioned document a nearly identical model was created. In addition to the creation of a pullout test that can use the finite element analysis software Abaqus. The author of the document provided several visuals as well that helped confirmed the accuracy of model in Abaqus. Below is the drawing of the subject that will experience the pullout test. From the drawing the appropriate dimensions for the model can be obtained in this case a block and a rebar.

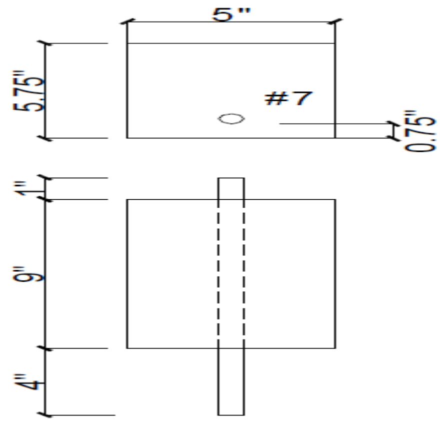


Figure 3: Drawing of Pullout Test Subject (Li 2007)

After observing the dimensions provided they can be inputted into Abaqus to produce a model of the block with the rebar through it. Additionally, even more information is necessary to create a proper model. Provided below are such important aspects needed to proceed in Abaqus.

Table 1: Material Properties (Li 2007)

	Modulus of Elasticity, E (psi)	Poisson's Ratio, ν	Density, ρ (lb/in^3)
Concrete	4.42×10^6	0.15	0.086
Steel	29×10^6	0.32	0.286

The material properties are extremely essential for simulating how the model will behave throughout the analysis. Assigning the properties of concrete to the block and steel to the bar are steps that need to be taken in the Abaqus program. Also in this document was a figure that provided a visual of the example. With the below figure as an aid as well as other information obtained in the thesis the appropriate model orientation, mesh data, details on where the boundary conditions need to be applied, and how the load needs to be applied can be gathered.

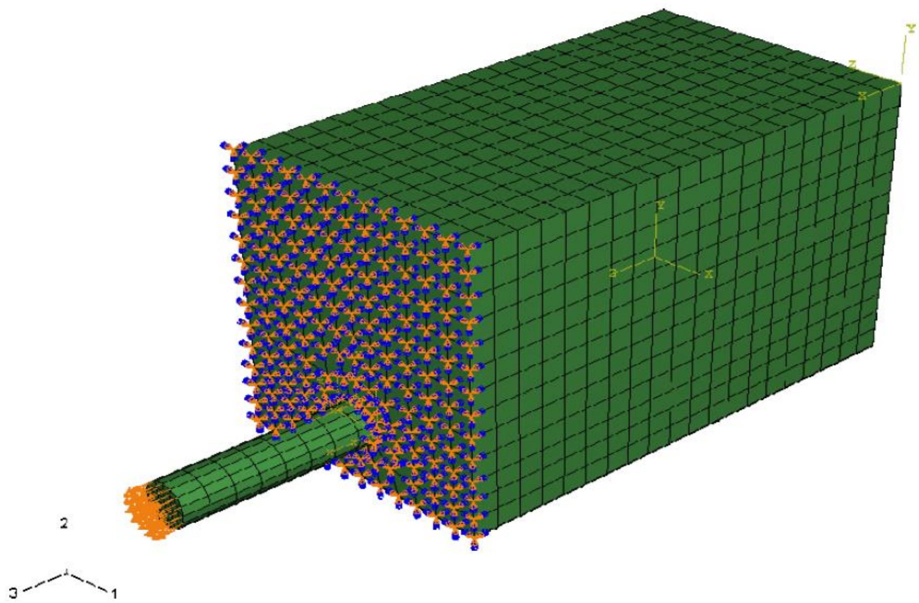


Figure 4: Fully Assembled Model (Li 2007)

A major factor in verifying the pullout procedure for further use in this project is comparing the results that the previous researcher obtained to the results gathered using their data as an example. In the example both the loads applied to the rebar and their respective displacements were documented as seen below.

Table 2: Load vs. Displacement from Example (Li 2007)

Load (lbs)	Displacement (in)
0	0
438.6	0.0080
578.7	0.0160
680.6	0.0240
763.6	0.0320
834.9	0.0400
834.9	0.1180

Reproduction of Numerical Analysis for Verification

The next step in the verification process is creating a new unique sample that simulates the same conditions as aforementioned experiment explored in the previous sections. The following presents the essential information that verifies the numerous analyses employed throughout the project.

Model Properties

Using the previous data from the experiment as a basis, a model can be designed and generated within Abaqus. Following the same procedure that was stated in the earlier section, initially Abaqus requires the input of the model's dimensions. In this case the dimensions are the same as those used in Chapter 3 (Figure 3) as well as the elastic material properties of the model (Table 1). However, this particular case requires the need for the input of the plastic properties of both the concrete and steel materials.

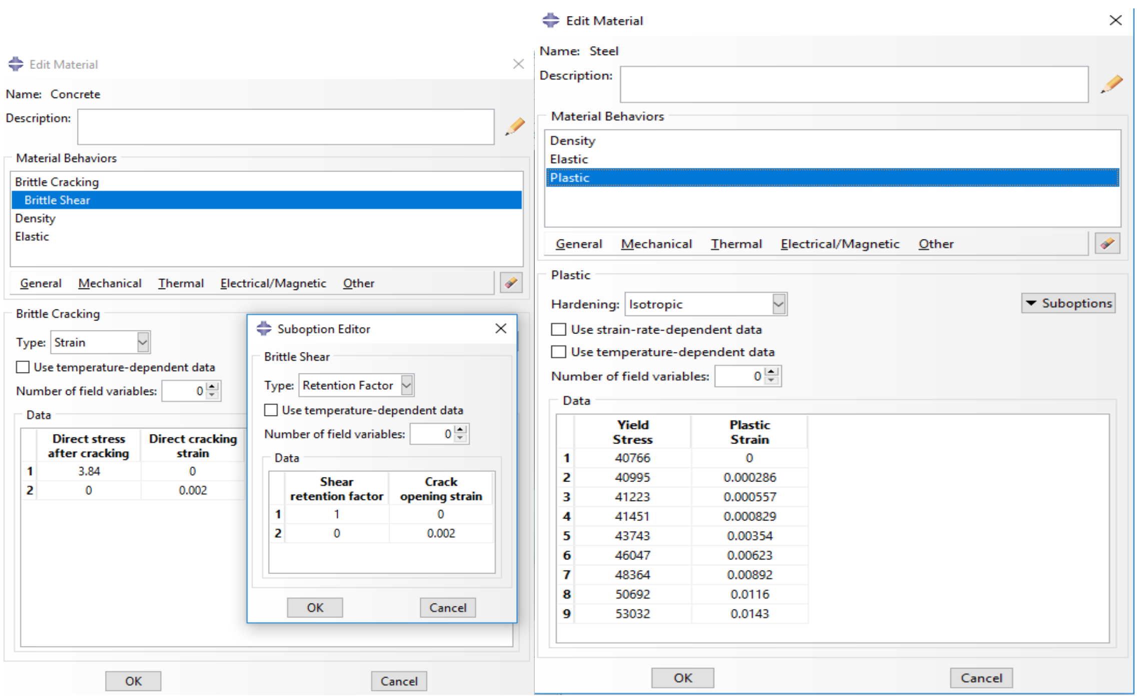


Figure 5: Plastic Properties of Concrete and Steel

Applying all of these properties for the materials within Abaqus is key for establishing the behavior of the model under any particular loading. Note that the units when entered are consistent with a variety of parameters such as significant figures as well as the measurement system. Mixing up feet and meters would cause significant errors. Below are parts of the process which are also important to obtain results.

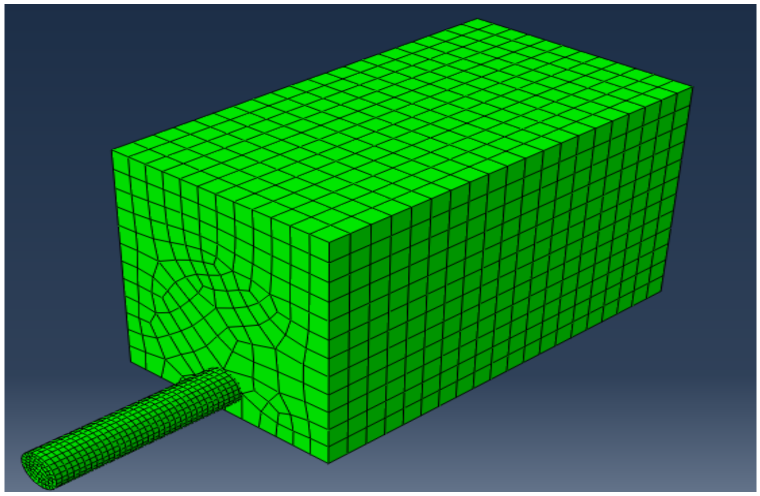


Figure 6: Full Assembly of Model with Mesh

Next the meshing of the model effects results drastically as well. The establishment of the mesh allows for a chance at obtaining more wisdom about the model's performance. After an analysis ends the mesh gives the user clear points that can be selected to get information and data on the model which can be used to describe the behavior at that node.

The applying of a boundary condition on the end of the steel bar can simulate the same effects of a legitimate pull out test. Boundary conditions also need to be placed on the face of block in the direction of the pull and at the opposite end of the bar in which the boundaries are fixed.

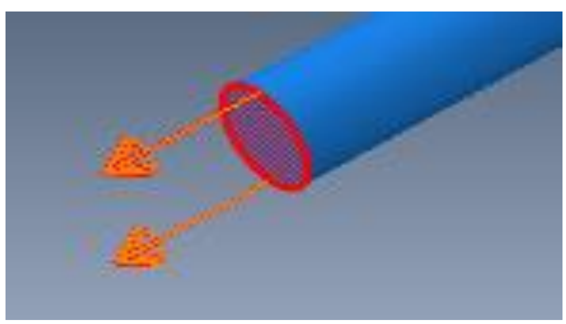


Figure 7: Pulling out of Bar in Pullout Test

Assigning the interaction properties is essential for getting the appropriate reaction during contact. In any real life experiment the bond between the concrete and steel is unique so when employing Abaqus to perform a finite element analysis using the interaction tab is necessary. Properly setting up the interaction with the type of contact, surfaces, and other interaction property can lead to more accurate results.

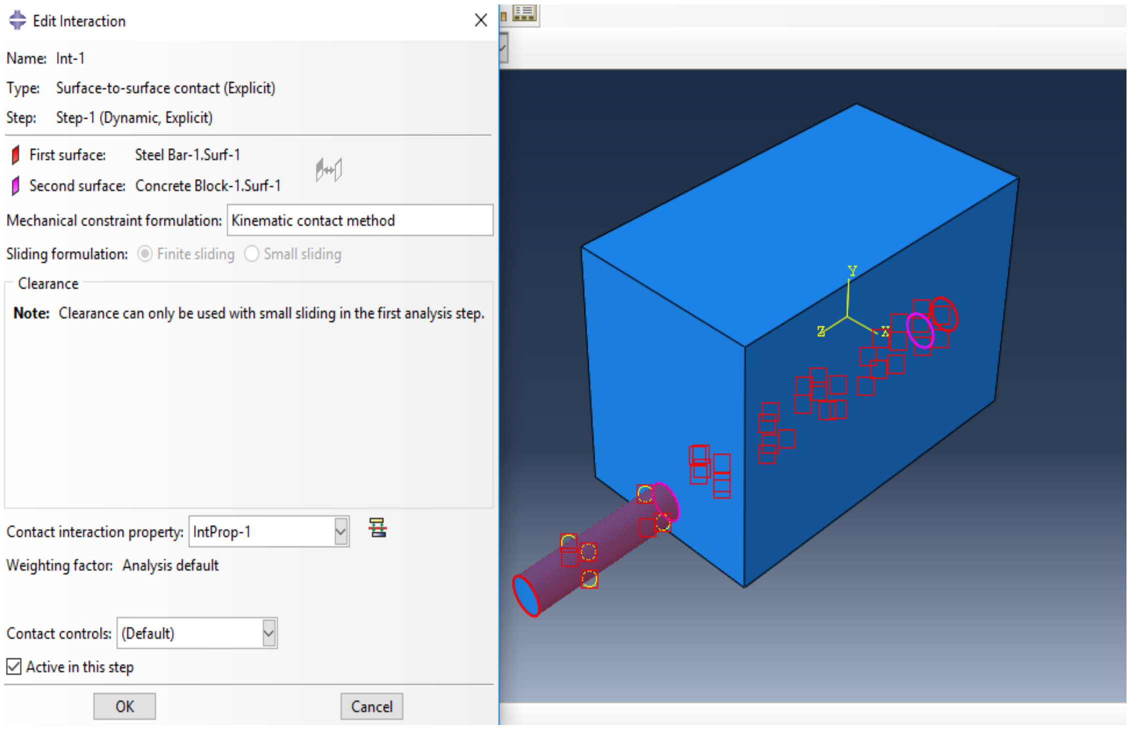


Figure 8: Interaction Properties of Model

Numerical Analysis Results

A major factor in verifying the pullout procedure for further use in this project is comparing the results that the previous researcher obtained to the results gathered using their data as an example. In this sample both the loads applied to the rebar and their respective displacements were documented as seen below.

Table 3: Load vs. Displacement of Abaqus Pullout Test

Load (lbs)	Displacement (in)
0	0
567.18	0.0050
796.07	0.0150
851.4	0.0299
884.86	0.0399
944.03	0.0549
975.8	0.0648
978.9	0.0799
973.4	0.0899

Comparison of Numerical Analysis Results

Comparatively speaking the values observed for the displacement do not differ much relatively speaking. The results produced by Abaqus showcase a graph that appears to be “stiffer” than the experimental results as it should be. Experimental tests have substantially more factors affecting results than their numerical analysis counterpart. Another important aspect to observe is the similarity of the shape between both curves showing those interested that the behavior in all practical load cases are the same.

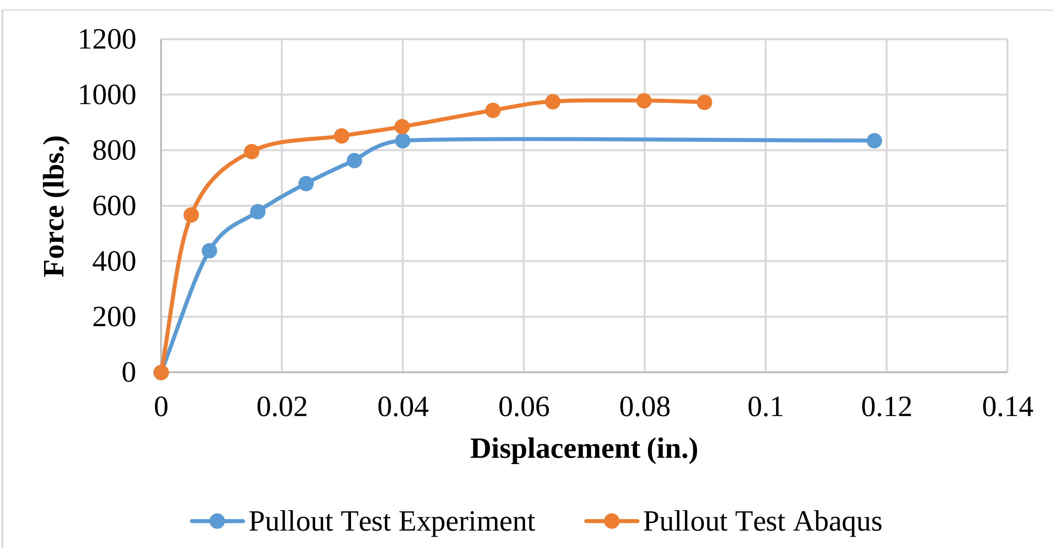


Figure 9: Load vs. Displacement Pullout Test Comparison

Table 4: Percent Difference between Experiment and Abaqus

Percent Difference (%)
0
0.29316
0.375618
0.250955
0.1588
0.13071
0.168732

Founding the percent difference between the experimental analysis and numerical analysis is another device that presents the accuracy at this point of the project which leads directly into the next important step.

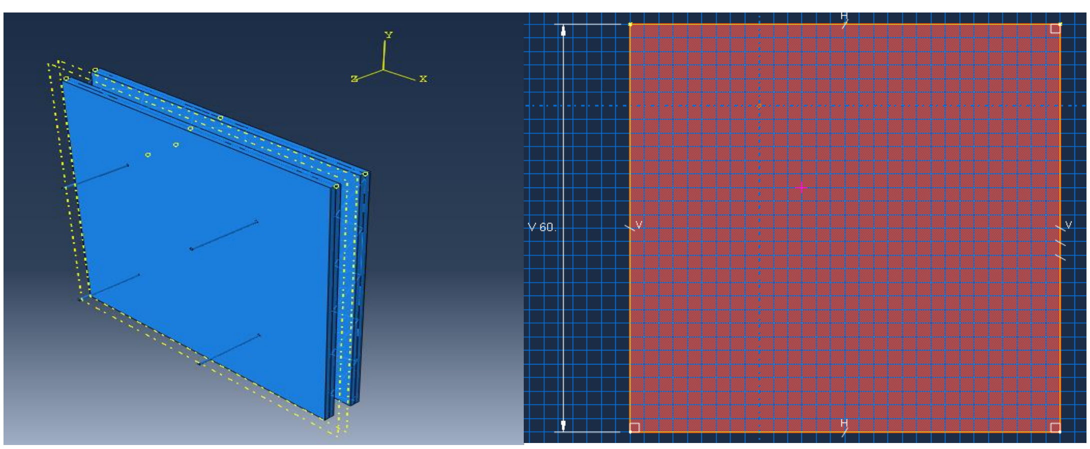
In this thesis the finite element model was developed to investigate the behavior of MSE wall panels. Abaqus is used for finite element analysis (FEA) of the welded wire wall panels for linear and nonlinear analysis. Abaqus is considered as a powerful FEA tool that allows users to analyze the behavior of concrete and steel wires in the wall facing. Abaqus/CAE was employed for creating the model of the welded wire panels, monitoring the analysis job, to view and post-process the results of the analyses, and Abaqus/Explicit was used for the analyses of the panels when highly non-linear materials are showcased in a model and it allows for the explicit integration scheme to solve a system of equations in very small time increments through numerous steps and allows models to undergo large deformations.

Modeling of 3D Welded Wire Panel

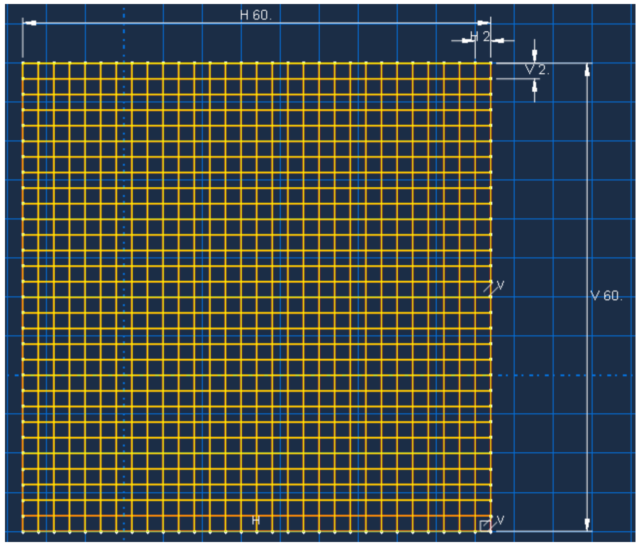
Having the aforementioned verification completed, the next phase of this work was conducted. With the knowledge of the appropriate practices and techniques needed to create an accurate model a model of a 3D welded wire panel was established in Abaqus.

Geometric Modeling and Boundary Conditions

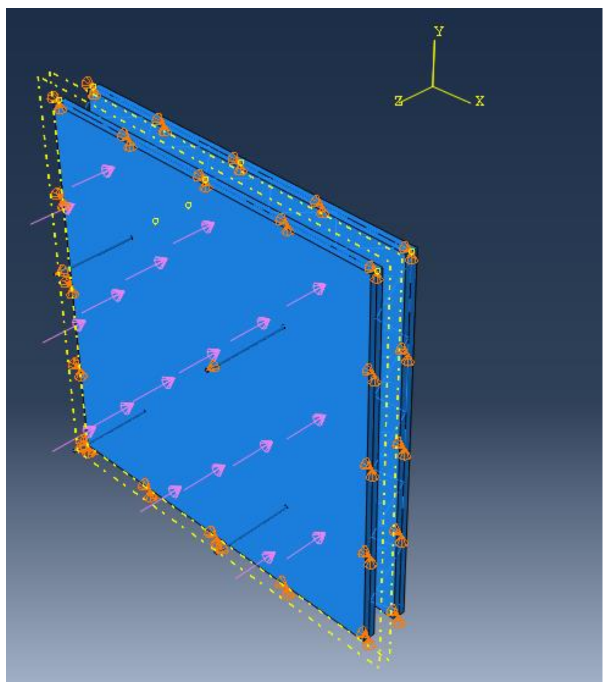
Three-dimensional solid elements were used to model the panels. The concrete layers and steel anchorage system were modelled using three-dimensional solid elements. The welded wire steel mesh and diagonal truss members were considered as beam elements. Two concrete layers were modeled, one layer in each side of the wall and were designed as 5x5 feet square layers with different spacing between the layers. The steel anchors are composed of steel bars and steel plates which were placed inside the concrete layers. The steel plates are 6x6 inches square steel plates and have ¼ inch thickness. Steel wire mesh were originally considered 18-inch diameter welded wires with a spacing of 2x2 inches (Figure 10). Another consideration for the model were the diagonal truss members with 18-inch diameter made of steel wires attached to each mesh in both concrete layers. Boundary conditions simulating each panel as a part of the wall facing was included in the modeling process. The in plane degrees of freedom (x and y direction) were constrained leaving the z direction perpendicular to the wall and free to move. Note that on the bar portion of each anchor only the z direction restricted. Note that in some models an expanded polystyrene (EPS) block was included.



(a)Panel



(b)Welded Wire Mesh

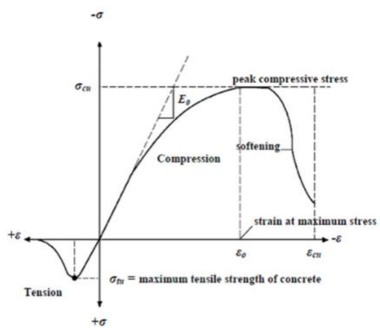


(c)Boundary Conditions

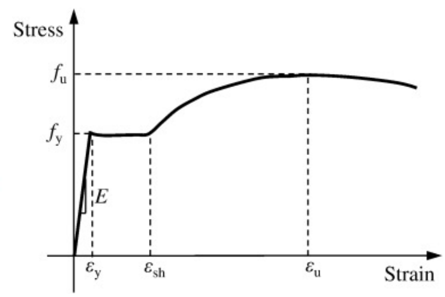
Figure 10: Facing Wall Details

Material Modeling

In an effort to capture the proper behavior of experimentally tested welded wire panels with the FE model, the material components incorporated into the FE model had to accurately describe the properties of the constituted materials and the interactions that take place between them. The behavior of concrete and steel materials are depicted in Figure 11. The materials properties are summarized in Table 5 and 6.



(a) Concrete



(b) Steel

Figure 11: Stress-Strain Curve

Table 5: Material Property for Concrete

	Density ρ (lb/In3)	Modulus of Elasticity E (psi)	Poissons' Ratio, v
Concrete	0.086	3289355	0.15

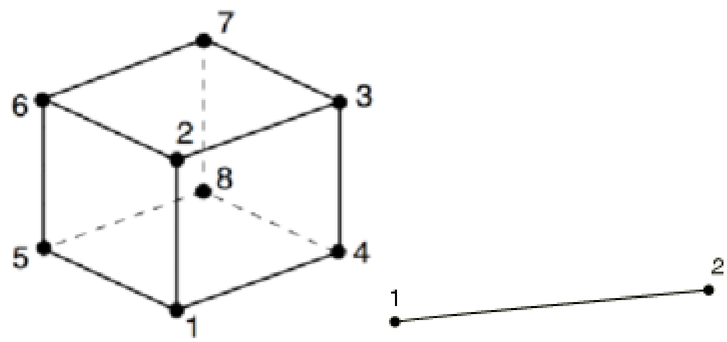
Table 6: Material Property for Steel

	Density ρ (lb/In3)	Modulus of Elasticity E (psi)	Poissons' Ratio, v	f_y (psi)	f_u (psi)	ε_y	ε_u
Steel	0.284	29000000	0.32	50000	68000	0	0.0112

Additionally, the inclusion of a modeled bond between the steel reinforcement and concrete layers are of great importance. In the FE model the perfect bond assumption was employed by embedding the steel elements including the mesh anchors within concrete layers using the embedded element option available in Abaqus. This option imposes a perfect bond between reinforcement and the surrounding concrete by rigidly connecting the nodes of the reinforcing elements to the nodes of the concrete layers creating an ideal situation that simulates the interaction of both materials within the welded wire panel. Also it is important to note that the EPS material mentioned previously has a 500 psi modulus of elasticity.

Element Types

In order to model the solid elements for concrete layers and anchorage system the reduced integration elements (C3D8R) were employed. Employing reduced integration elements is an effective option as this element is a 3D hexahedral shaped eight node linear brick elements with reduced integration. The elements have three degrees of freedom at each node meaning possible translations and rotations in the local x, y, and z direction at each node. The mesh size for solid elements are optimized for time of analysis and the precision of results. The steel wire mesh and steel diagonals were modelled using the two node linear beam elements (B31) (Figure 12).



(a) Solid Element (b) Beam Element

Figure 12: Elements

Nonlinear Finite Element Analysis

A step-by-step analysis was performed to investigate the behavior and performance of the panels in linear and nonlinear domains. The amount of load/deflections are increased in each step gradually to have a better understanding of the behavior of panels.

Other Modeling Cases

Aside from the aforementioned 5x5 model that was, designed additional models, with various design parameters, were created and analyzed. In the following chapter, the results of the analysis for the other cases are presented and thoroughly discussed.

Building the Model

For this thesis, constructing the panel gradually was deemed appropriate. Meaning each component of the panel was created and subjected to FE analysis. This way the behavior of the panel after each component is made can be observed. The figures below showcases each step in building the panel until the 5x5 ft. 3D welded wire panel is achieved.

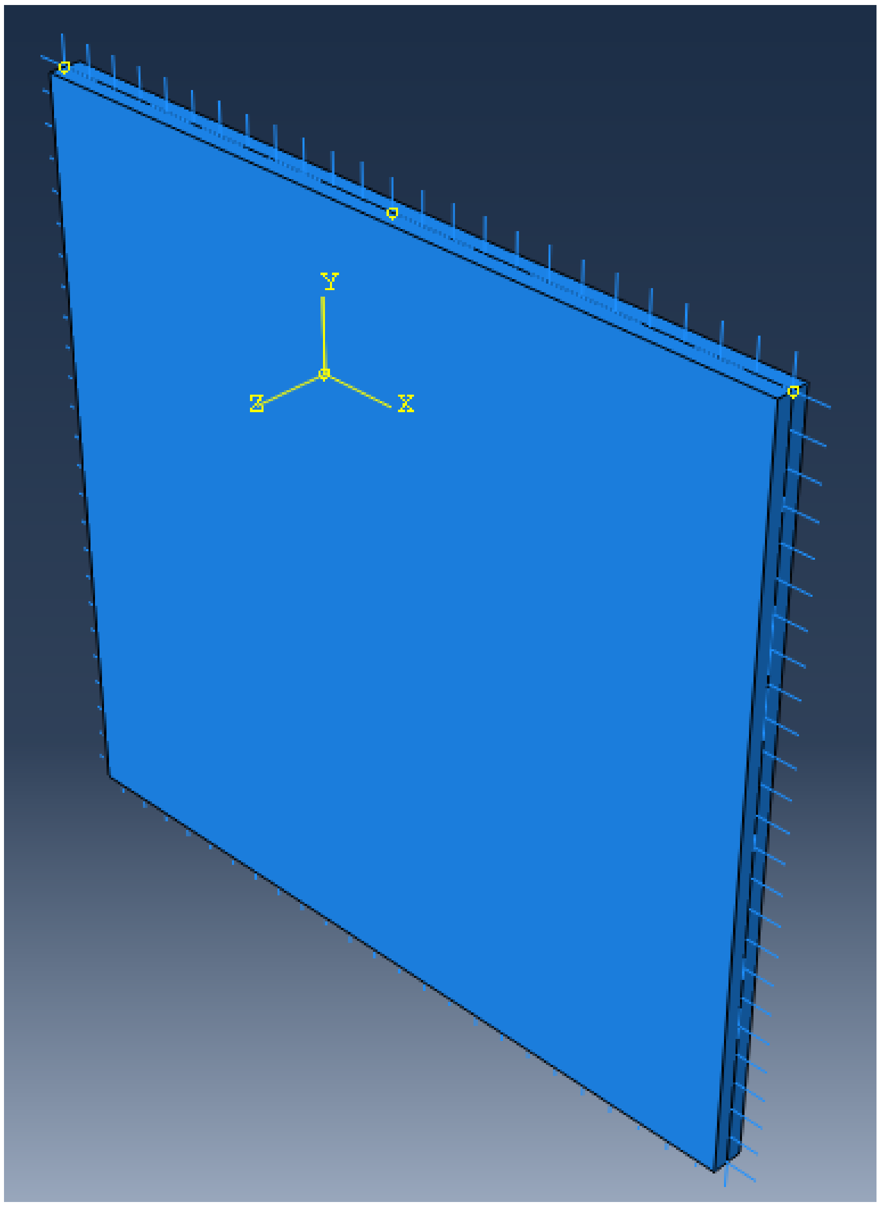


Figure 13: Concrete Layer with Steel Mesh

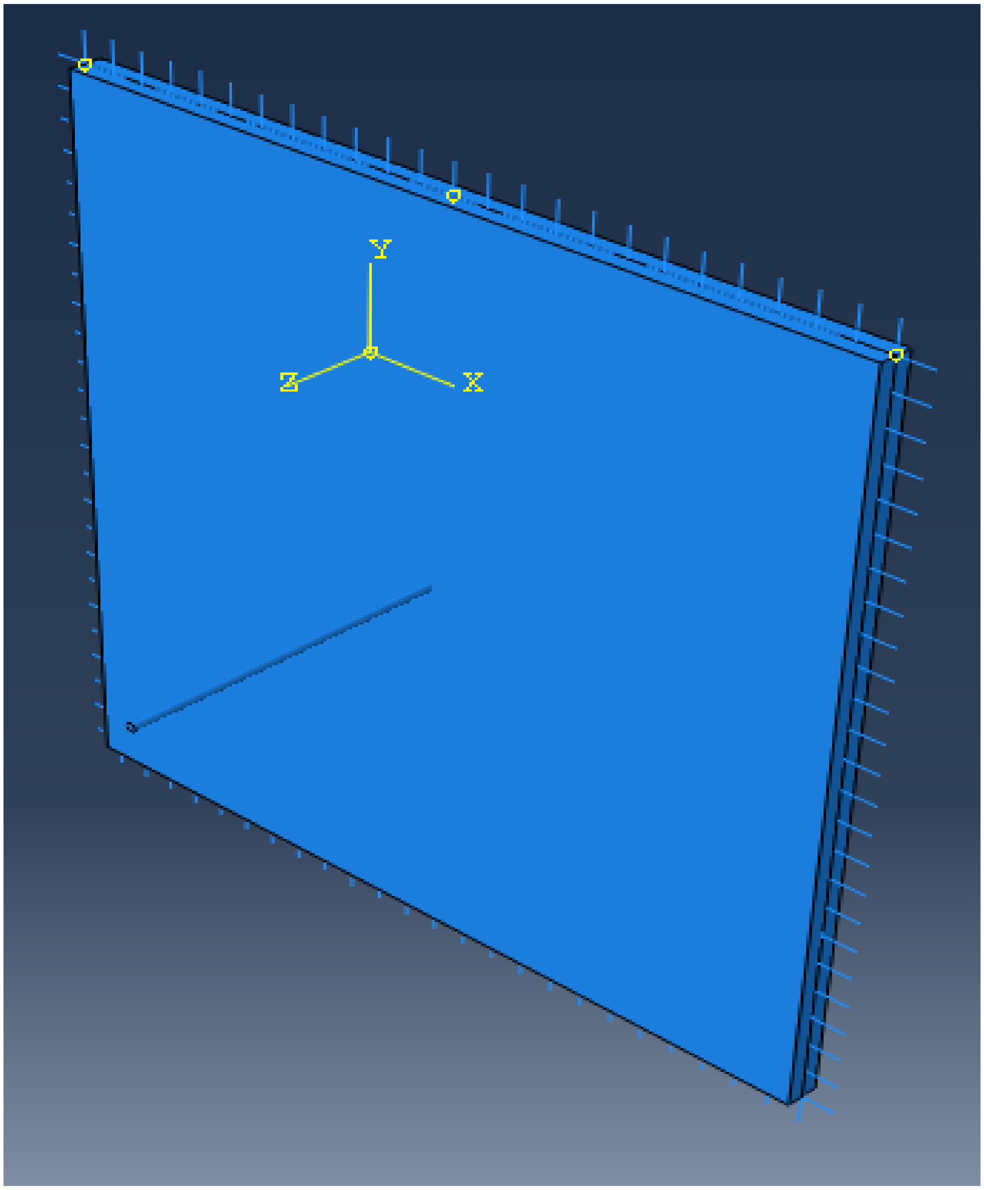


Figure 14: Concrete Layer and Steel Mesh with One Anchor

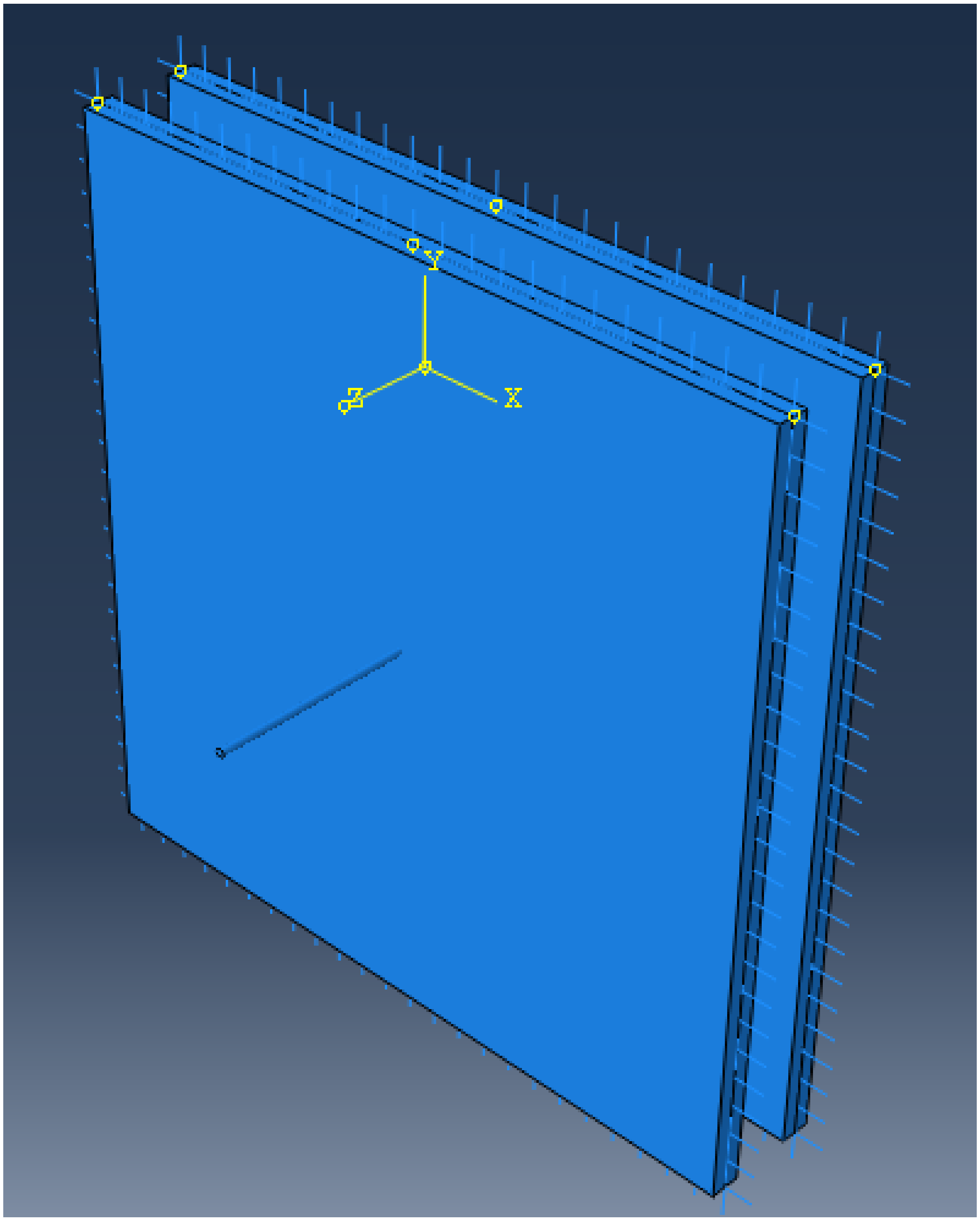


Figure 15: Two Concrete Layers and Steel Mesh with One Anchor

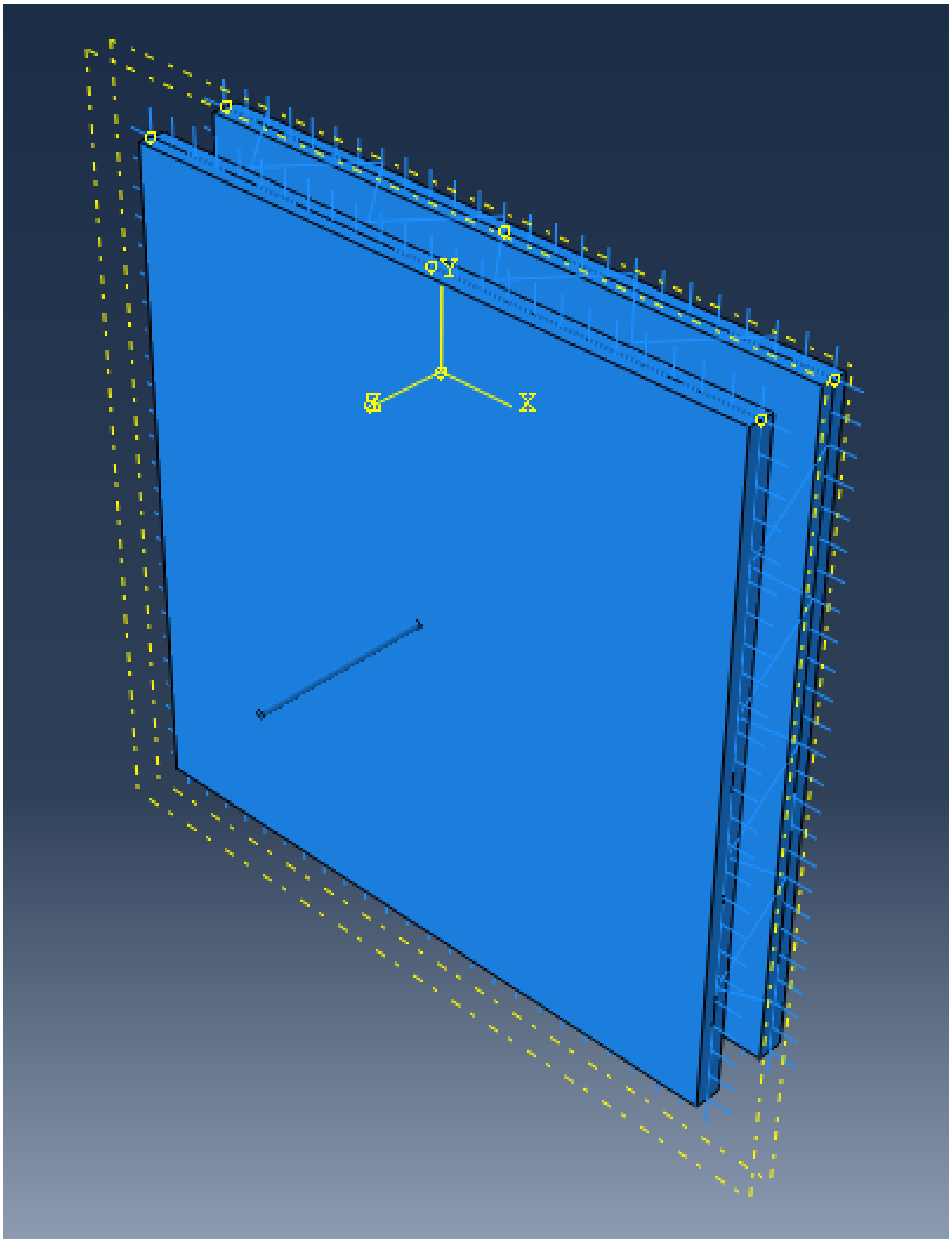


Figure 16: Two Concrete Layers and Steel Mesh with One Anchor and Steel Diagonals

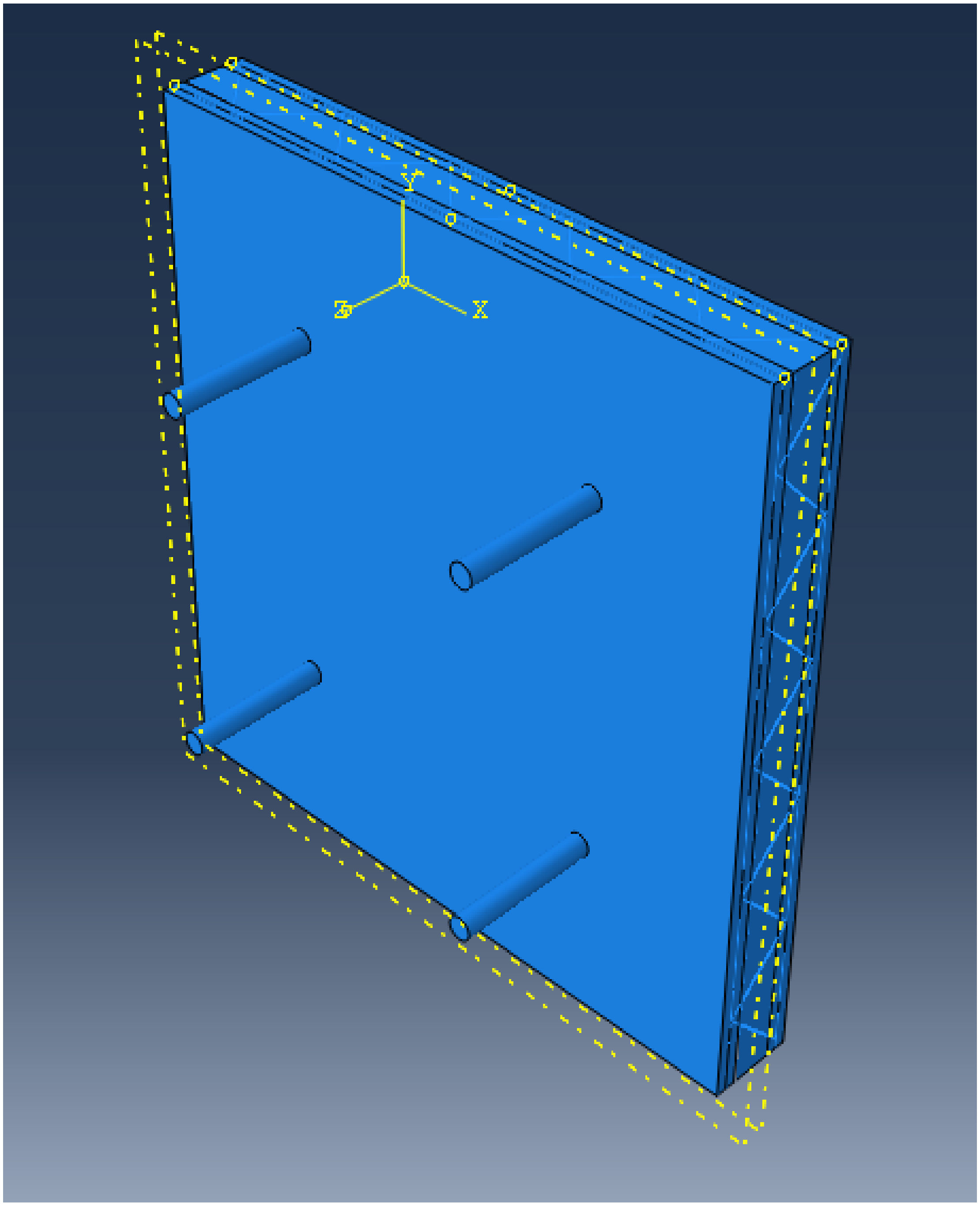


Figure 17: Full 5x5 ft. 3D Welded Wire Panel

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the numerical model results from the varying 3D welded wire panels are presented and compared. The results display the general behavior of the models using pressure versus deformation curves, and maximum stress versus soil pressure of the different components of the panels. Figures 18, 19, and 20 showcase the general details of all the models examined within this chapter. Figure 18 displays the steel mesh, which is in cased within the concrete layers of each model. In all cases the steel mesh has 2x2 inch openings and have a square shape. The sides of the steel mesh vary depending on the size of the concrete layers, this is represented with the variable A.

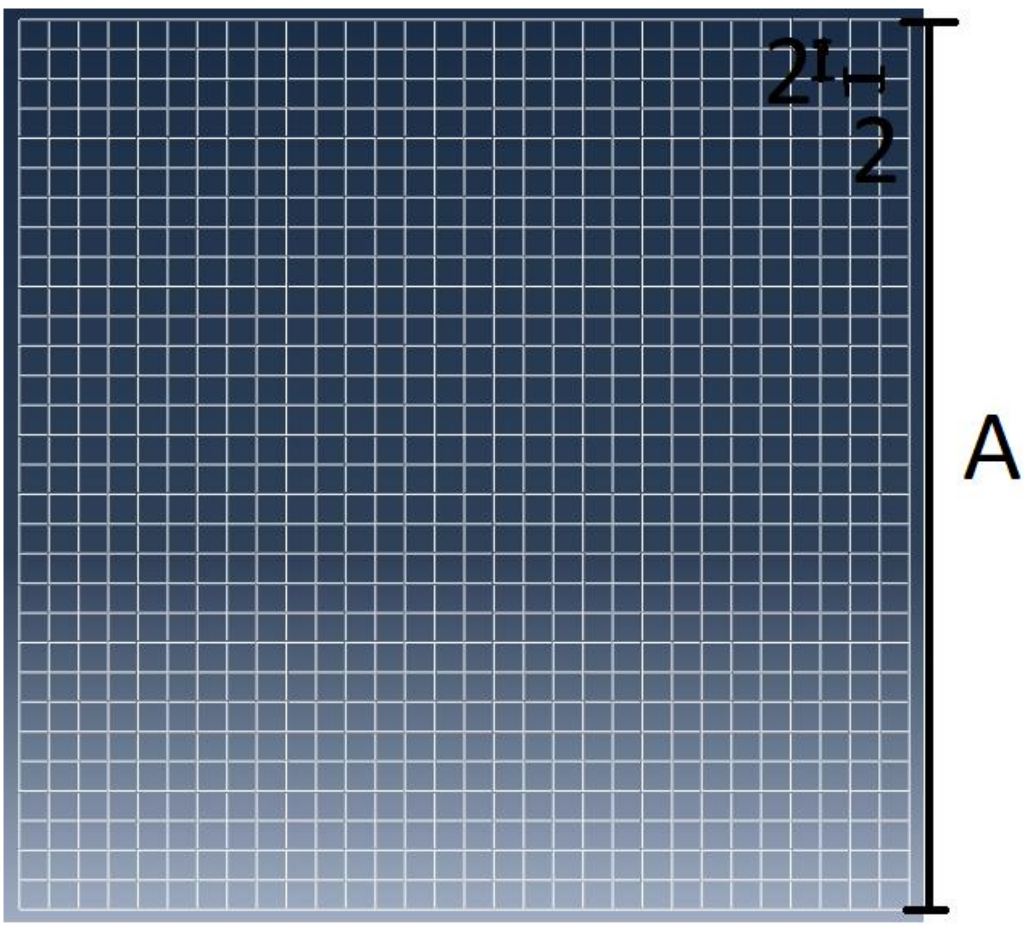


Figure 18: Steel Mesh within the Concrete Layers of All Models

Figure 19 displays the steel component of the 3D welded wire panel. There are the two steel mesh layers that are within the concrete. Between the two steel mesh layers, there are steel diagonals, which are created with the same steel wires as the steel mesh. The steel diagonals are spaced 2 inches apart and all around the sides of the steel mesh.

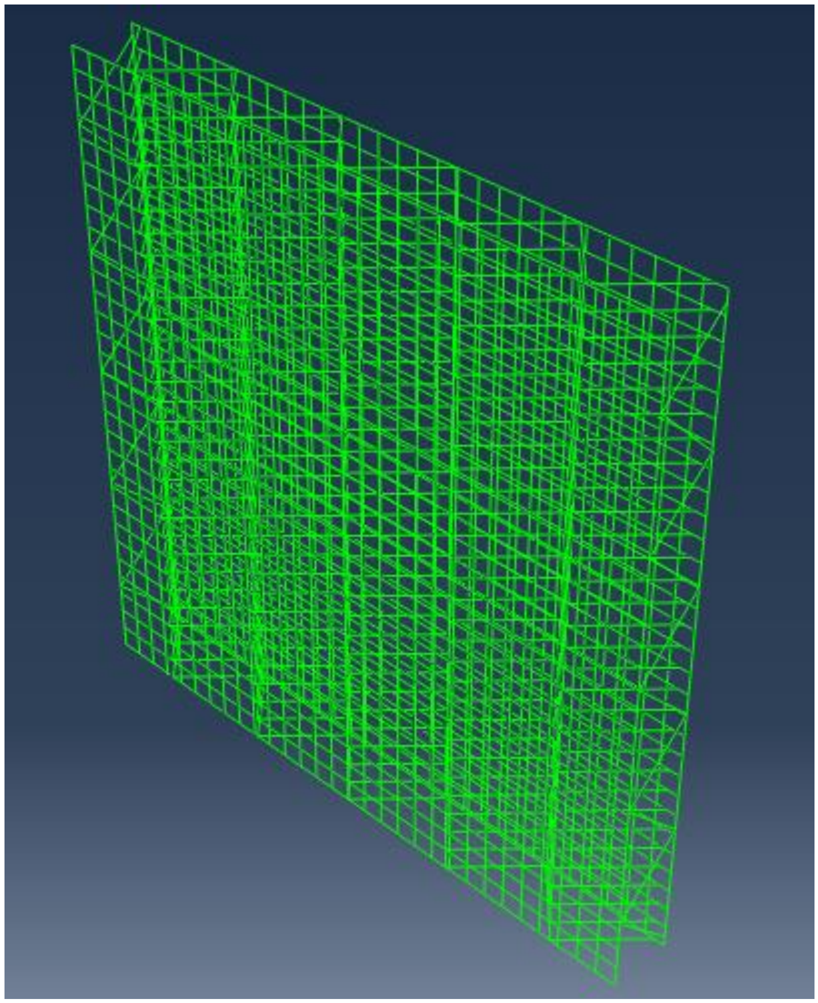


Figure 19: Steel Part of All Models

Figure 20 is a picture of the full 3D welded wire panel with the anchor, concrete layers, steel mesh, steel diagonals, and EPS. Note in some of the analysis in this chapter there is no EPS layer. In figure 20 "A" represents the length of each side on the panel. In all cases the length of the sides for the concrete layers, steel mesh and EPS are equal. "d" represents the distance between the concrete layer which varies throughout this work. The variable “d” can also represent the EPS thickness.

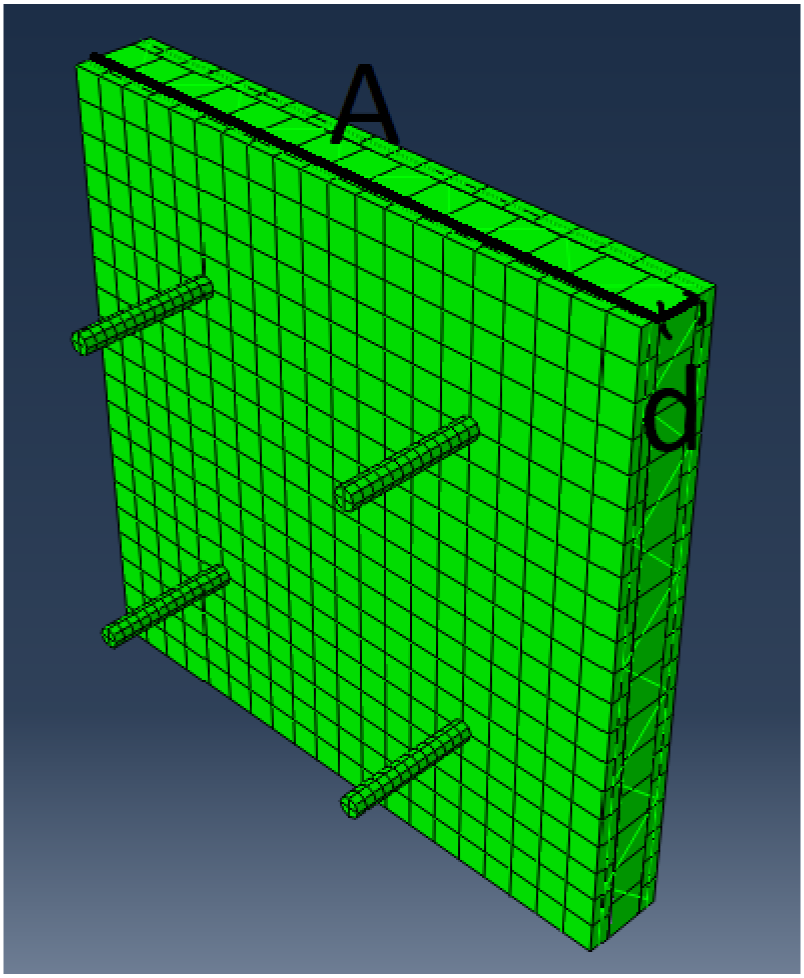


Figure 20: Full Panel

5x5 ft. 3D Welded Wire Panel

Employing the model from Chapter 3, a finite element analysis was conducted. Figure 21 will show the soil pressure versus maximum stress relationship in the steel component of the panel. While figure 22 displays the soil pressure versus maximum stress relationship in the steel diagonals of the panel.

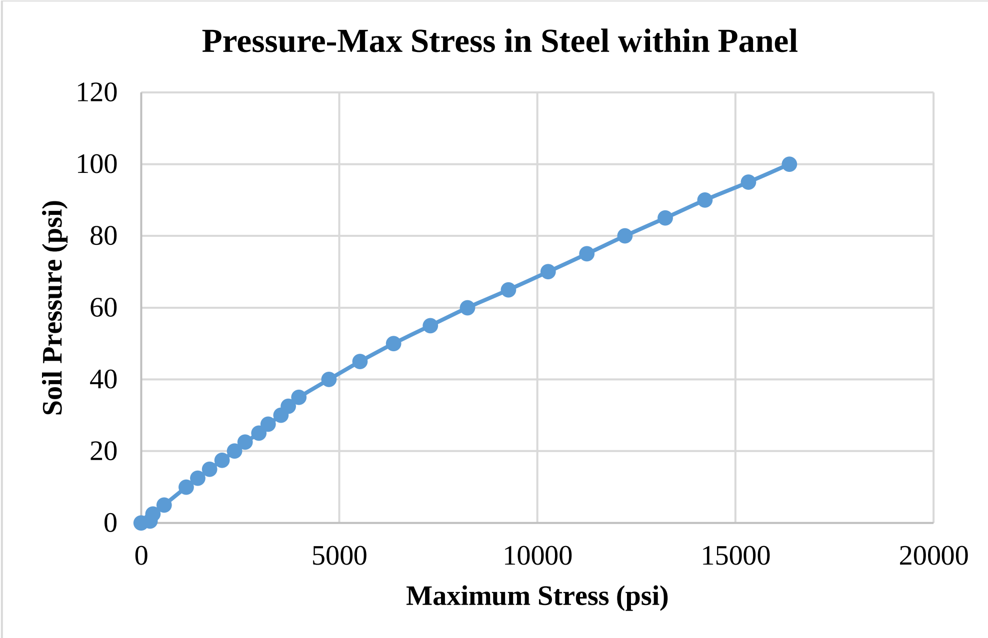


Figure 21: Pressure vs. Maximum Stress of Steel in 3D Welded Wire Panel

Figure 21 is a representation of the relationship between the soil pressure applied on the welded panel in psi and the maximum stress found in the steel component of the panel. Observing this behavior can verify whether or not the model functioning appropriately. Experimental test results that have been conducted in the past have shown that steel should yield as it approaches it's specified yielding stress. In this case the yielding stress is 50,000 psi. As Figure 21 details as the soil pressure and stress increases the steel begins to yield.

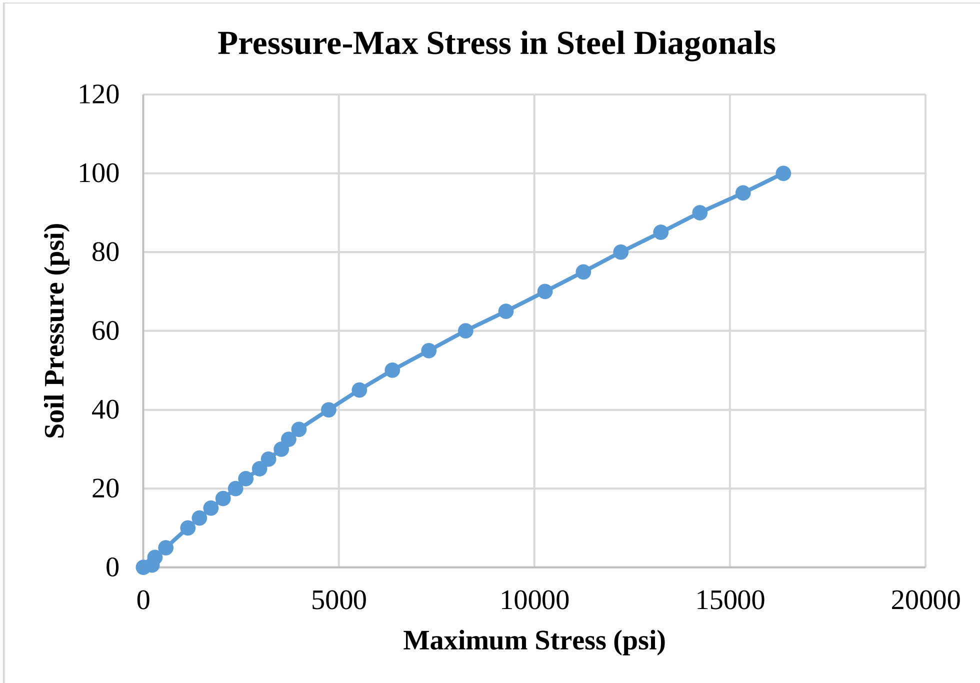


Figure 22: Pressure vs. Maximum Stress of Steel Diagonals in 3D Welded Wire Panel

Figure 22 is a representation of the relationship between the soil pressure applied on the welded panel in psi and the maximum stress found in the steel diagonals of the panel. As stated previously observing this behavior can verify whether or not the model functioning appropriately if the results correspond with experimental test results and show that steel yields as it approaches its specified yielding stress (50,000 psi). As Figure 22 details as the soil pressure and stress increases the steel begins to yield. Note that the stress in the diagonals turns out to have maximum stress of the steel throughout the entirety of the 3D welded wire panel. Based on the results the maximum stress found in the steel mesh are not the controlling factor of the panel yielding. The design the diagonals in the panels have more importance in this case. If improvements to the panel are needed perhaps, the attention should be focused on increasing the strength of the steel in the diagonals or increasing the diameter of the diagonals. In addition to examining the stresses in the panel the deformation of the panel was observed as well (Figure 23).

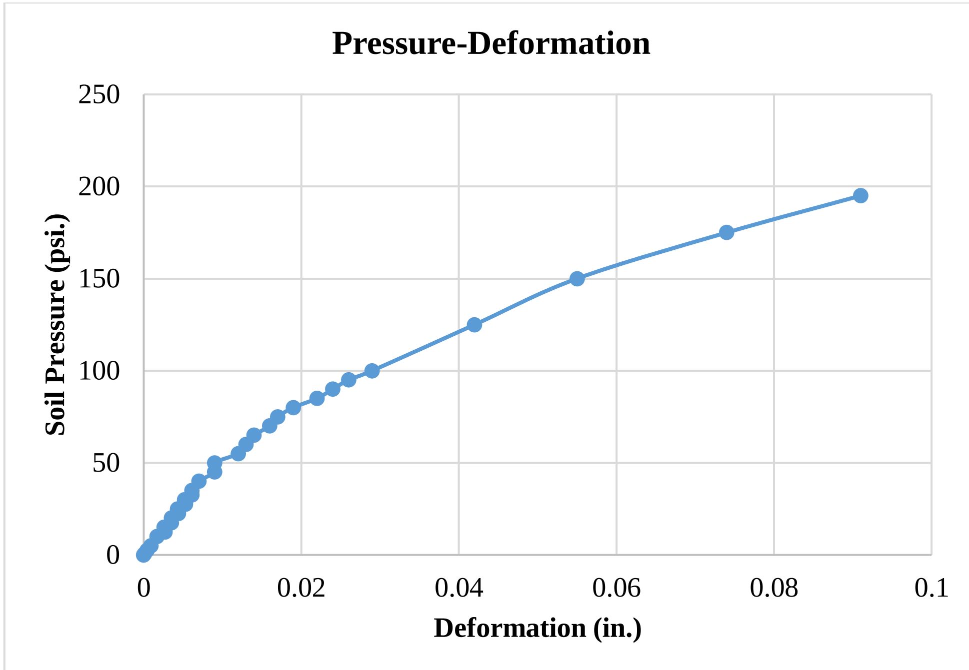


Figure 23: Pressure vs. Corner Deformation of 3D Welded Wire Panel

The above figure is the results of the finite element testing of the deformation of the load facing concrete layer of the 3D welded wire panel as the soil pressure on that layer increases. In figure 23, the vertical axis represents the soil pressure on the panel (psi) and the horizontal axis represents the deformation of the corner of the concrete layer with respect to the anchorage that the pressure is acting on (in). It can be observed that the load versus deflection behavior has three segments: un-cracked, cracked concrete, pre yield and post yield of steel. The un-cracked phase shows a significant rise in the load with small increases in deformation. The cracked phase of the results show that as the concrete begins to crack and the deformation increases significantly with the increase of load. After the yielding of the wires the deformation increases even more rapidly with increases in soil pressure.

4x4 ft. 3D Welded Wire Panel

The next model that was tested used the same exact conditions as the previous one. This model is a 4x4 ft. 3D welded wire panel. The anchorage system, boundary conditions, load applied, mesh, and elements are identical to the previous case. The only variants for this model is that the concrete layers are dimensioned as a 4x4 ft. square and the reinforced steel mesh in each concrete layer has been dimensioned to 4x4 ft. as well but still retaining 2x2 in. openings. Figure 24 is the 4x4 ft. model as it appears within Abaqus. While figure 25 is the soil pressure versus the corner deformation of the panel.

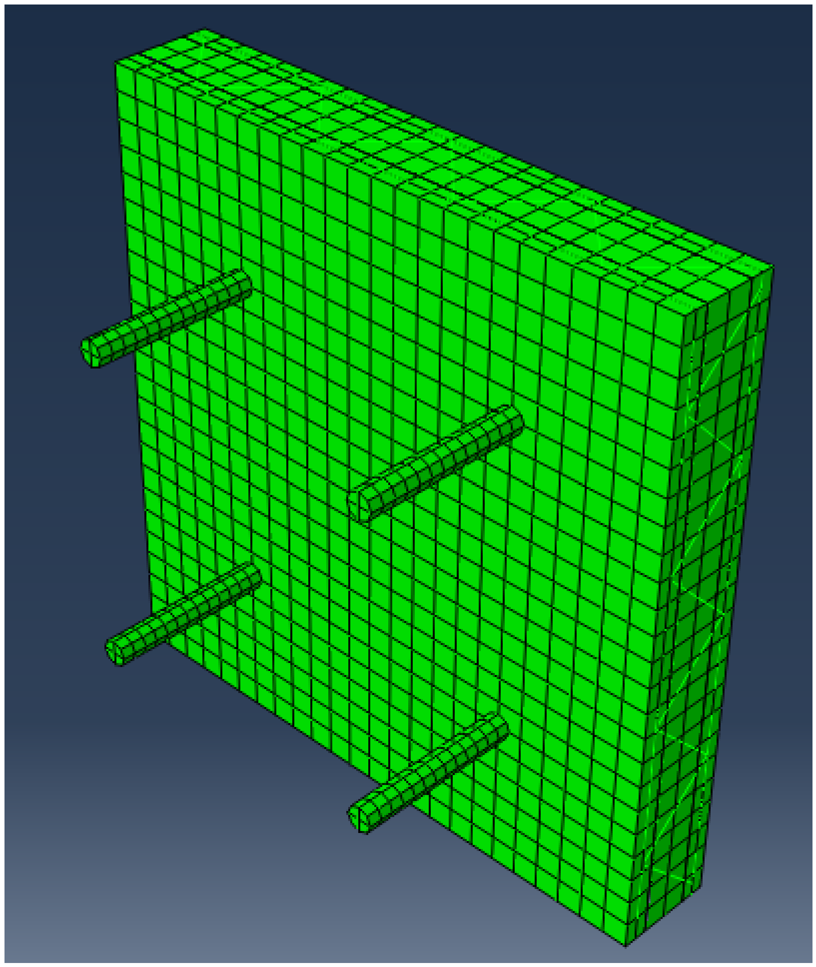


Figure 24: 4x4 ft. 3D Welded Wire Panel

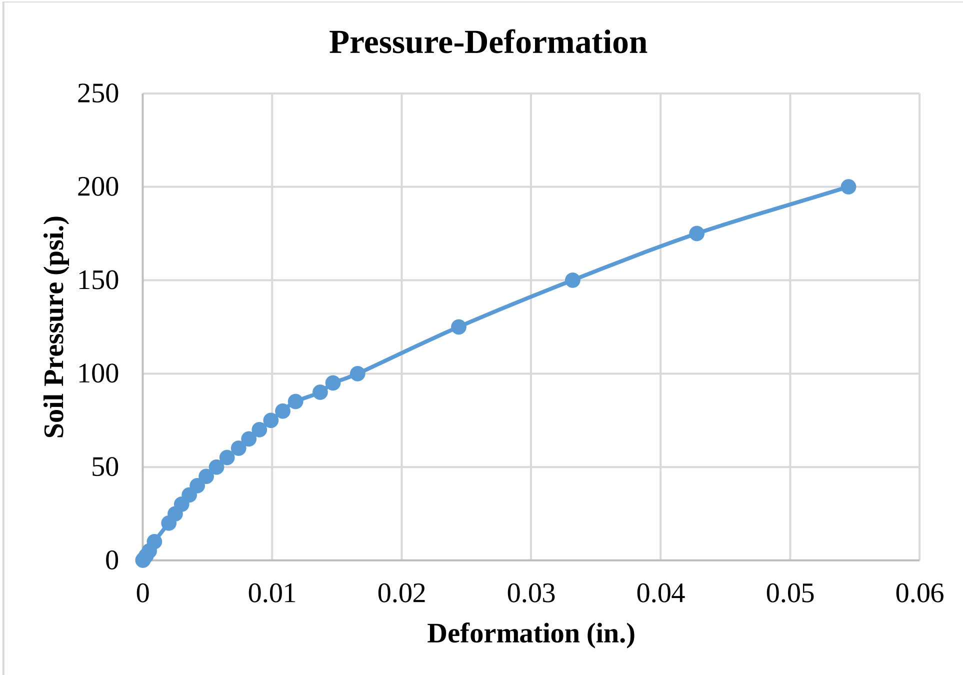


Figure 25: Pressure vs. Corner Deformation of 4x4 ft. 3D Welded Wire Panel

Through Abaqus, a finite element analysis of this model was completed. Figure 25 displays the results generated from the software. Both the horizontal and vertical axes are the same as the previous figure. The results shown in Figure 25 display a similar behavior to the results generated for Figure 24. There a rapid rise in the graph as the soil pressure increases, followed by the slight bending of the curve until the yield point is reached. After this point, the deformation increases more rapidly.

Solid Concrete Panel

Another model that was tested used the same exact conditions as the previous models. This model is a solid concrete panel. The anchorage system, boundary conditions, load applied, mesh, and elements are identical to the previous case. In this case, the panel to be used as a facing has one concrete layer. Inside of that concrete layer is a reinforced steel mesh with 2 inch openings. The concrete was dimensioned as a 5ft. by 5ft. square 3 in. thick. These dimensions were gathered through research of typical market panels and specification requirements. The basis of the dimensions for this model was the 5x5 ft. panel made by TENSAR Figure 26 is showcases this model in Abaqus.

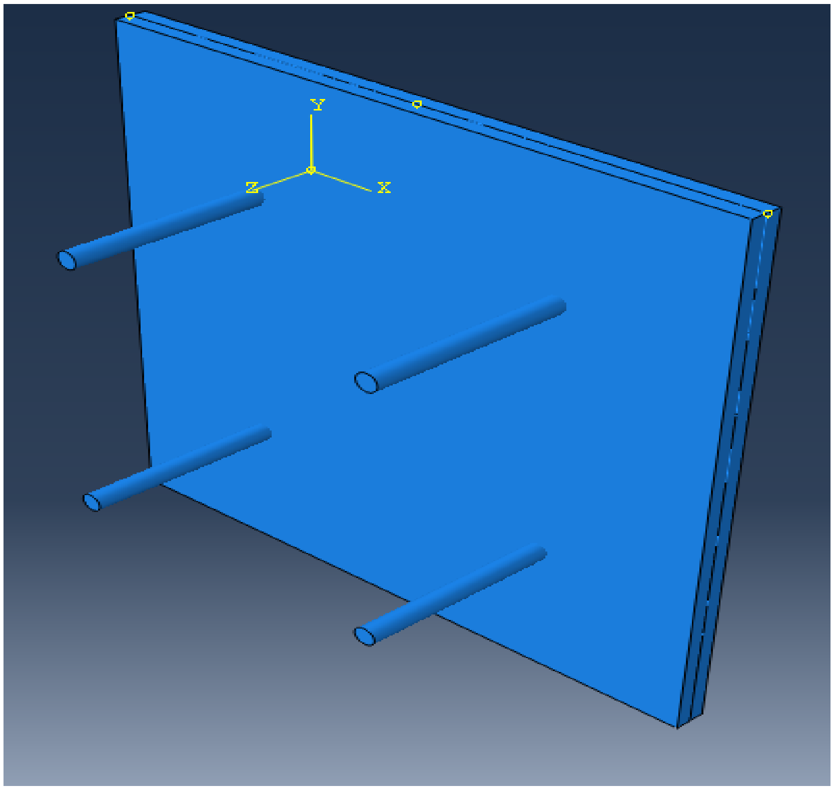


Figure 26: Solid Concrete Panel

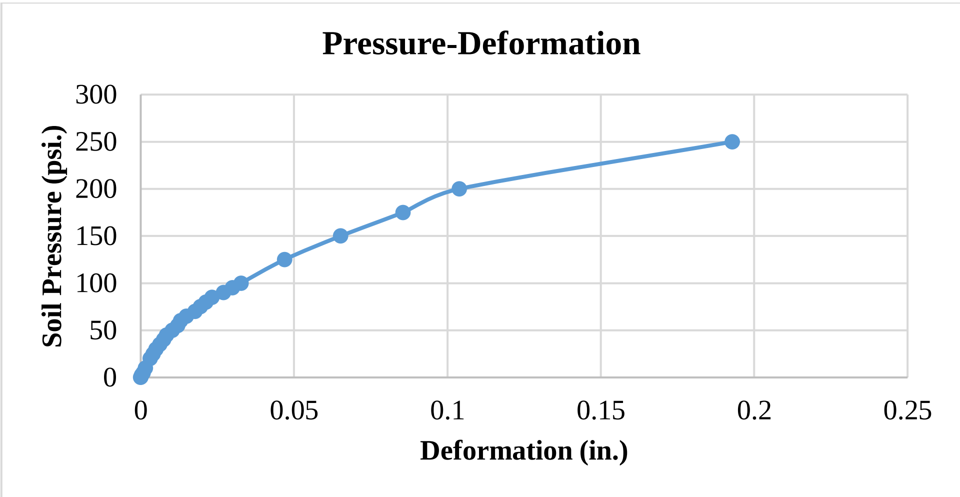


Figure 27: Pressure vs. Deformation of Solid Concrete Panel

The results of the FE analysis for the solid concrete panel in Abaqus are displayed in Figure 27. The horizontal axis represents the deformation of the corner of the concrete layer with respect to the anchorage that the pressure is acting on (in). and the vertical axis represents the soil pressure (psi) applied on the panel. Figure 27 displays a similar behavior to over pressure vs. deformation curves previously mentioned. The results reinforce that the model to behaving correctly in Abaqus as the concrete is acting within expectations in terms of cracking and yielding.

Comparisons of Varying Panel Geometries

The behavior of a 3D welded wire panel under soil pressure is an important parameter to consider. Examining numerous models with varying aspects are essential in determining the design of a panel. Special considerations also need to be observed for the yielding behavior of welded wire panel. The FE analysis results for the pressure vs. deformation curves of the aforementioned models were compared through the use of graphs in the following section. The figures below help articulate how variations in the 3D welded wire panels affect performance and behavior.

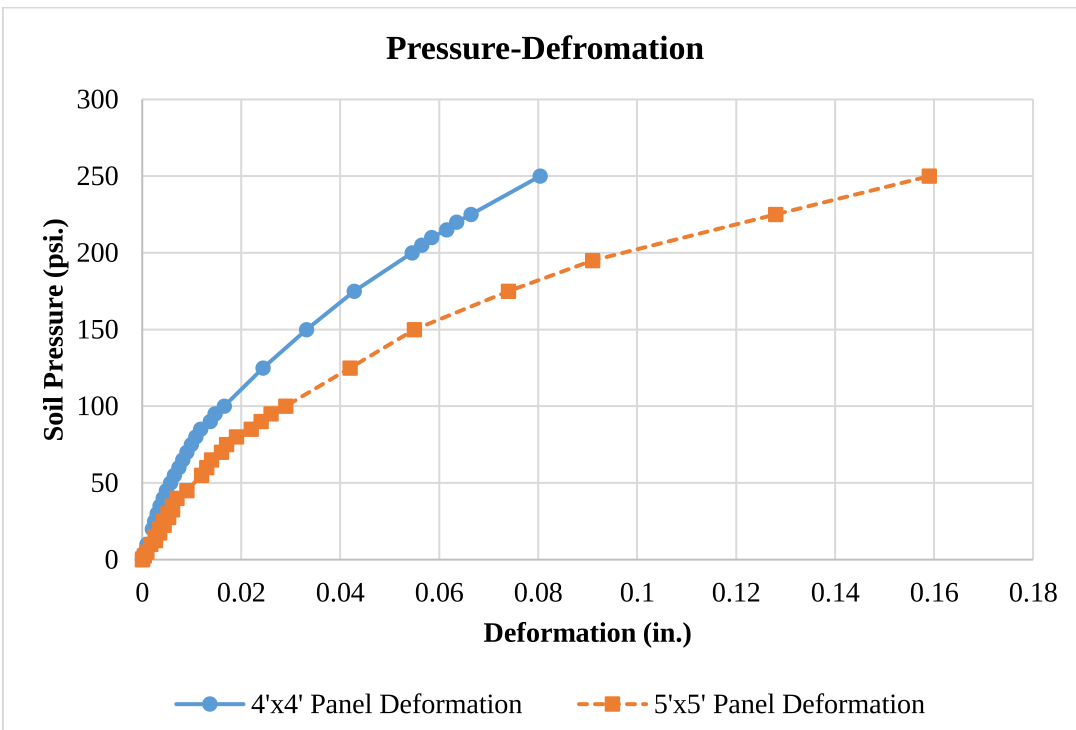


Figure 28: Pressure vs. Corner Deformation of Different Dimensioned Panels

Figure 28 displays the soil pressure vs. corner deformation curve for the models of the 4x4 ft. panel and the 5x5 ft. panel. Note that both panels are extremely similar in behavior before and after yielding. Both curves have the expected shape that represents the relationship of applied soil pressure and deformation. However, notice at each point when the soil pressure is the same on the curves that the deformation shown is different. The 4x4 ft. panel is “stiffer” is what can be interpreted from the results. From the results, when the soil pressure acting on the panel is 250 psi then the deformation for the 4x4 ft panel is 0.0804 in and the deformation for the 5x5 ft. panel is 0.159 in.

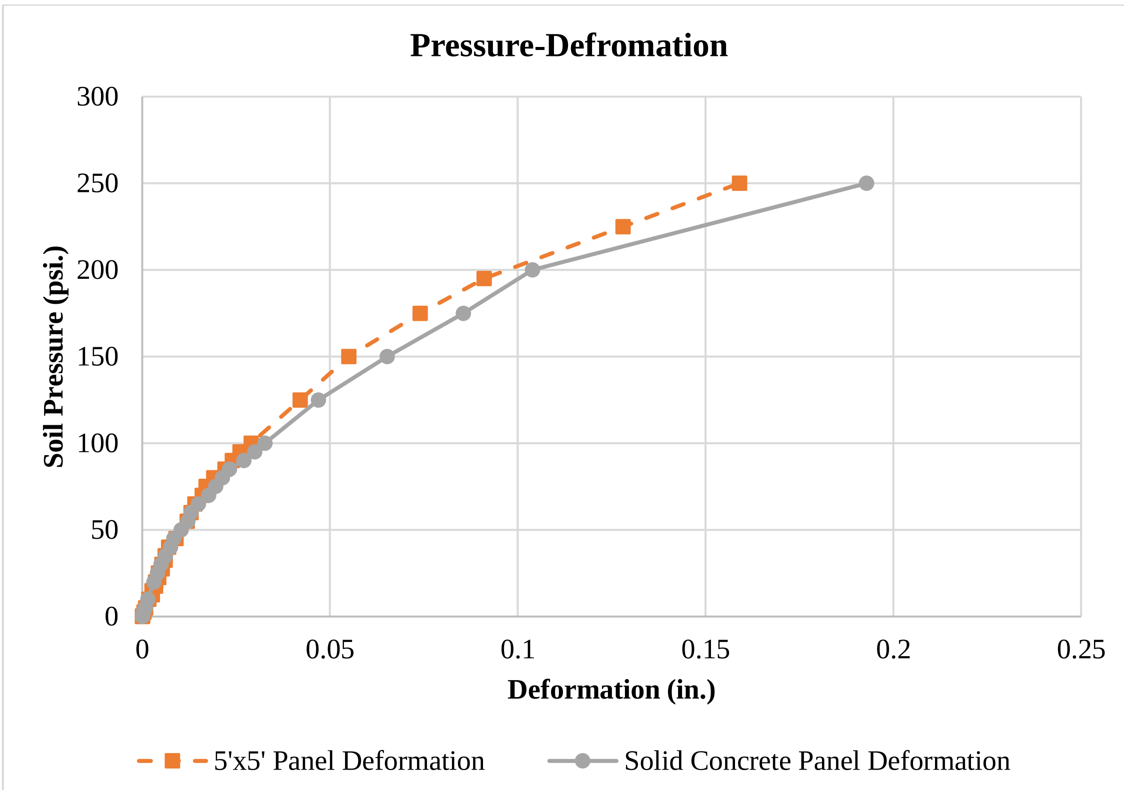


Figure 29: Pressure vs. Corner Deformation of Welded Wire Panel and Solid Concrete Panel

Figure 29 displays the soil pressure vs. corner deformation curve for the models of the 5x5 ft. panel and the solid concrete panel based loosely on TENSAR dimensions. Just like previously both panels are extremely similar in behavior before and after yielding. The curves gathered from both models are practically identical until yielding was approached. Both curves have the expected shape that represents the relationship of applied soil pressure and deformation. However, notice at each point when the soil pressure is the same on the curves that the deformation shown is different. The 5x5 ft. panel is "stiffer" is what can be interpreted from the results. When the soil pressure acting on the panel is 250 psi then the deformation for the 5x5 ft. panel is 0.159 in and the deformation for the solid concrete panel is 0.193 in.

Different Panel Spacing

In order to obtain a better understanding of the 3D welded wire panel additional models were created and analyzed. Compared to the other models previously discussed the models in this section will have different distances of spacing between the two concrete layers. The concrete was dimensioned as a 5ft. by 5ft. square 3 in. thick. The anchorage system, boundary conditions, load applied, mesh, and elements are the same as before. The spacing between the concrete layers are 2 inches, 4 inches, 6 inches, 8 inches, 10 inches, and a model with no spacing.

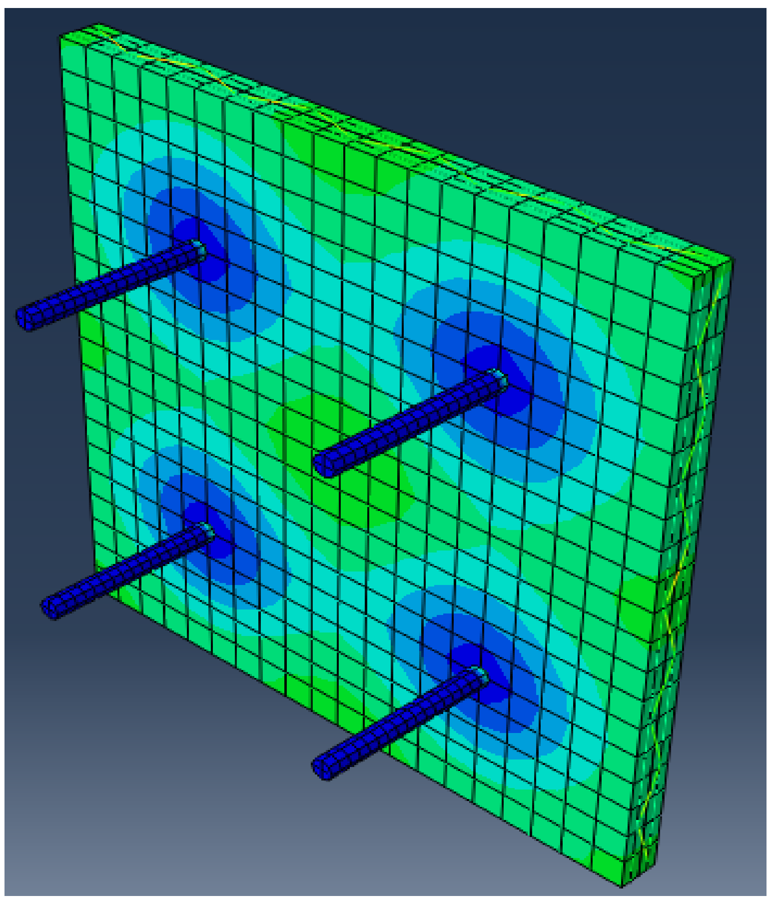


Figure 30: 3D Panel with 0 Inch Space between the Concrete Layers

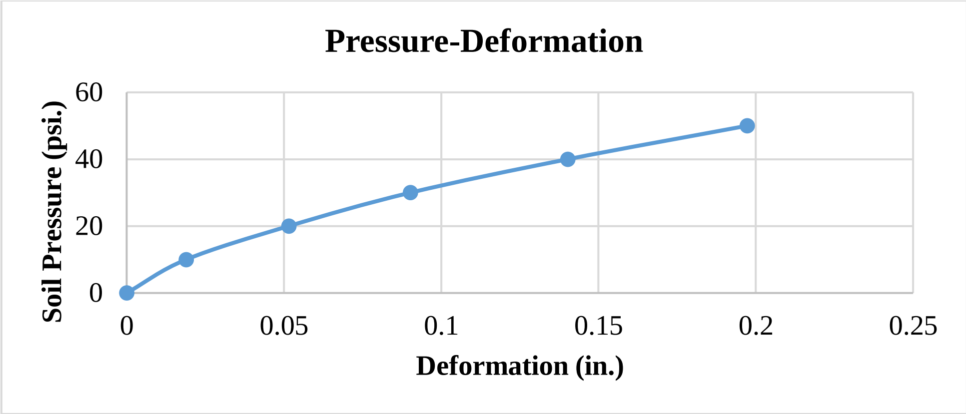


Figure 31: Pressure vs. Corner Deformation of Panel with 0 Inch Space between the Concrete Layers

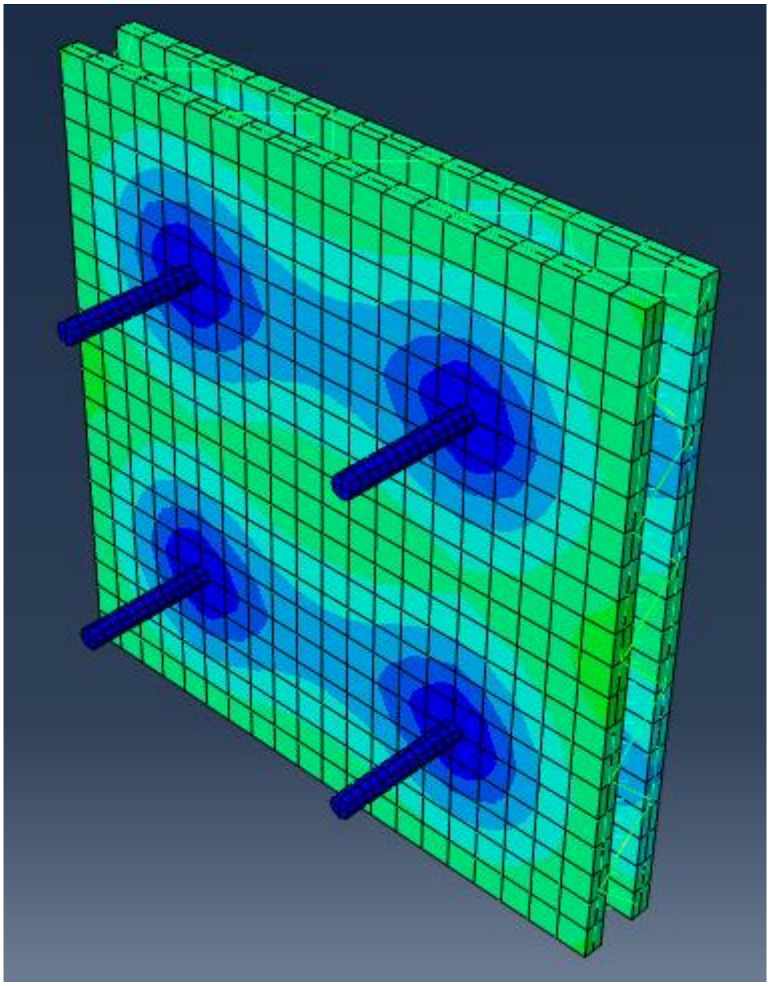


Figure 32: 3D Panel with 4 Inch Space between the Concrete Layers

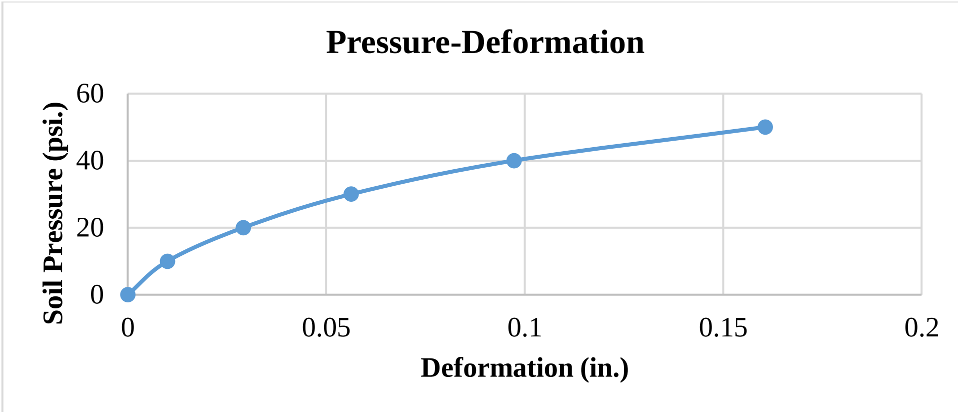


Figure 33: Pressure vs. Corner Deformation of Panel with 4 Inch Space between the Concrete Layers

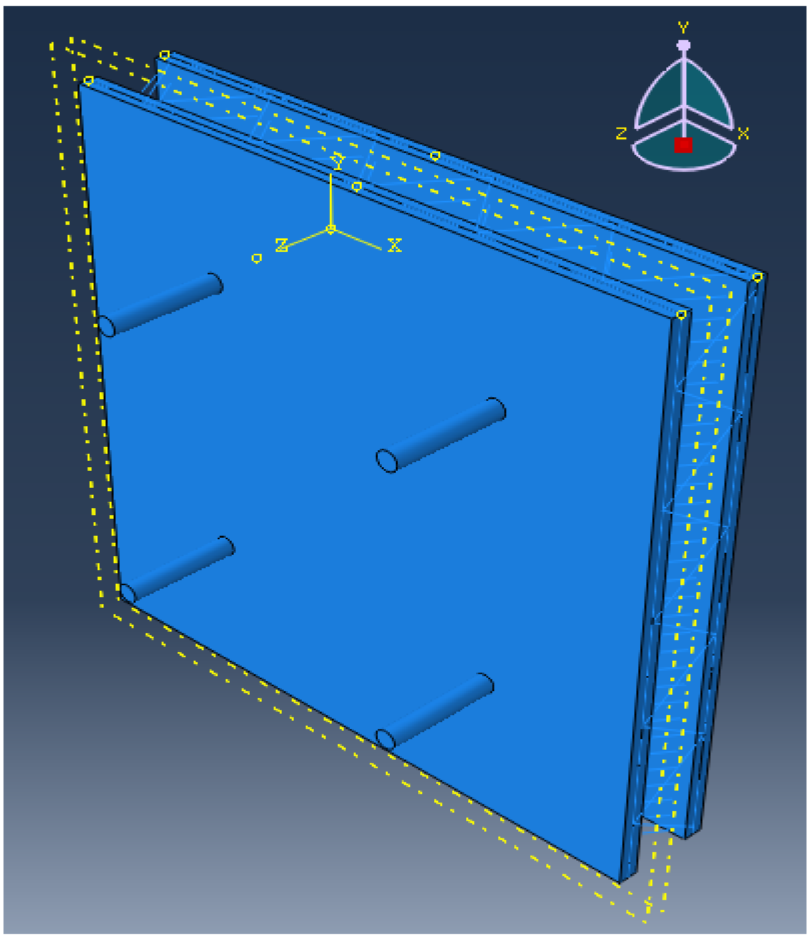


Figure 34: 3D Panel with 6 Inch Space between the Concrete Layers

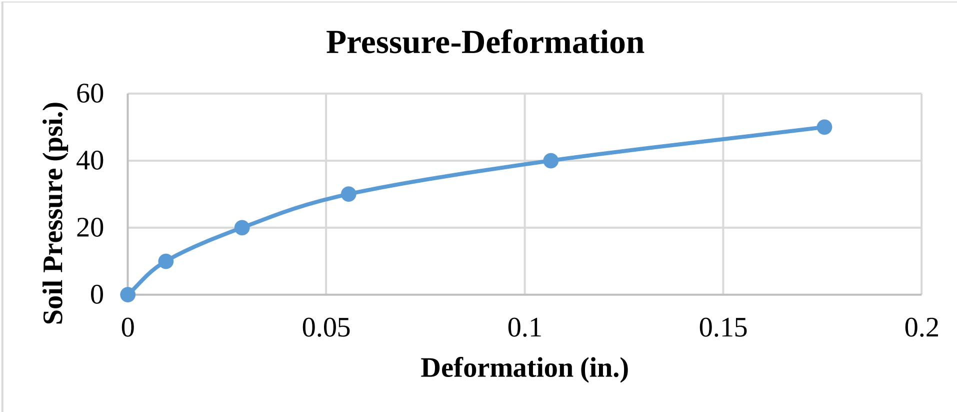


Figure 35: Pressure vs. Corner Deformation of Panel with 6 Inch Space between the Concrete Layers

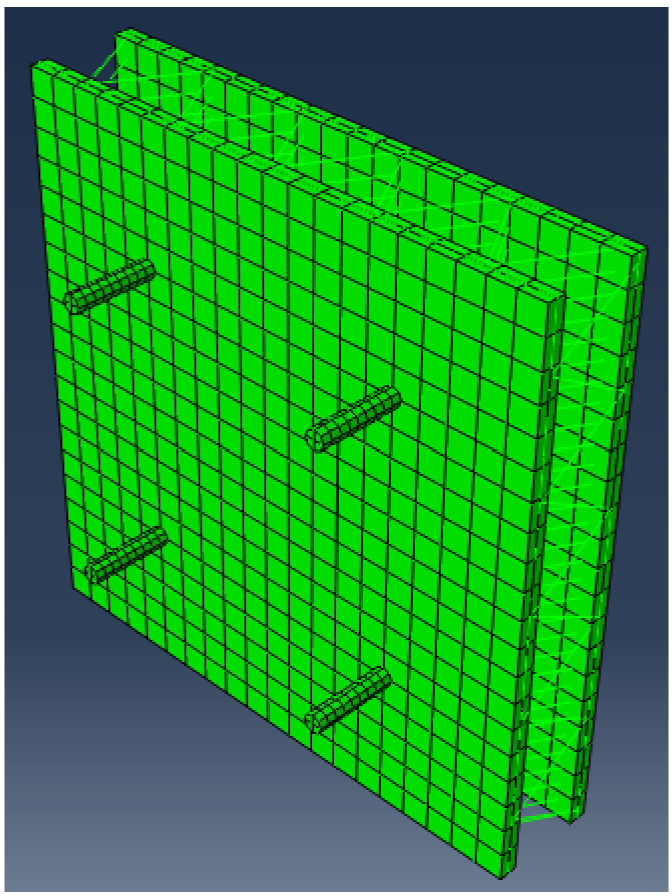


Figure 36: 3D Panel with 8 Inch Space between the Concrete Layers

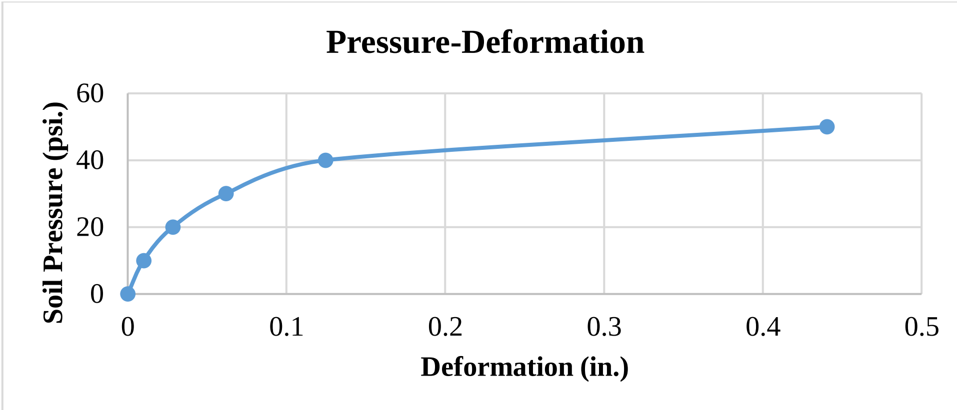


Figure 37: Pressure vs. Corner Deformation of Panel with 8 Inch Space between the Concrete Layers

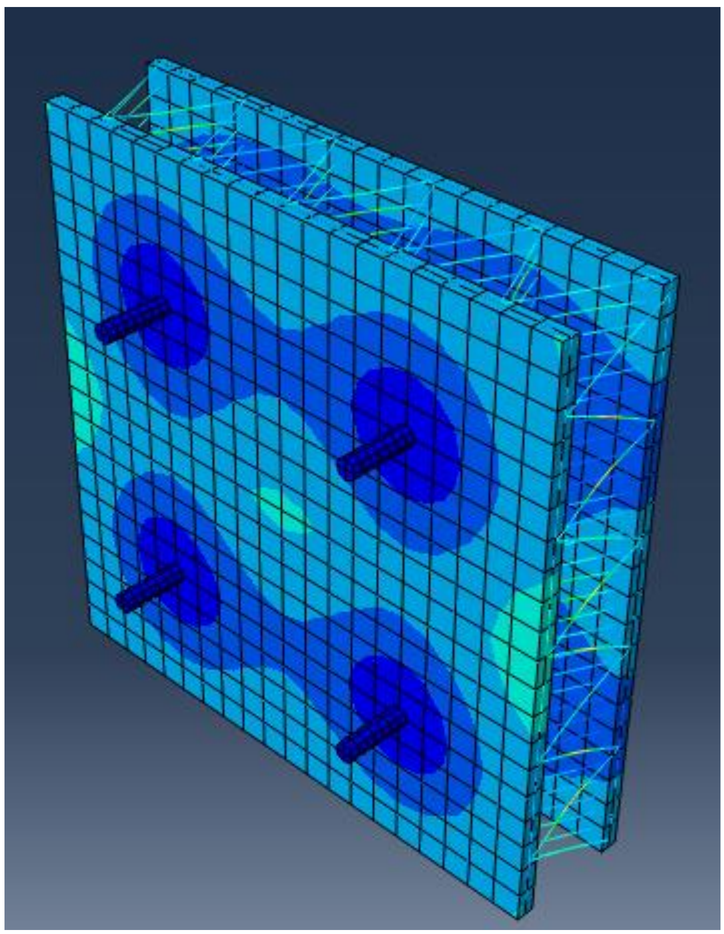


Figure 38: 3D Panel with 10 Inch Space between the Concrete Layers

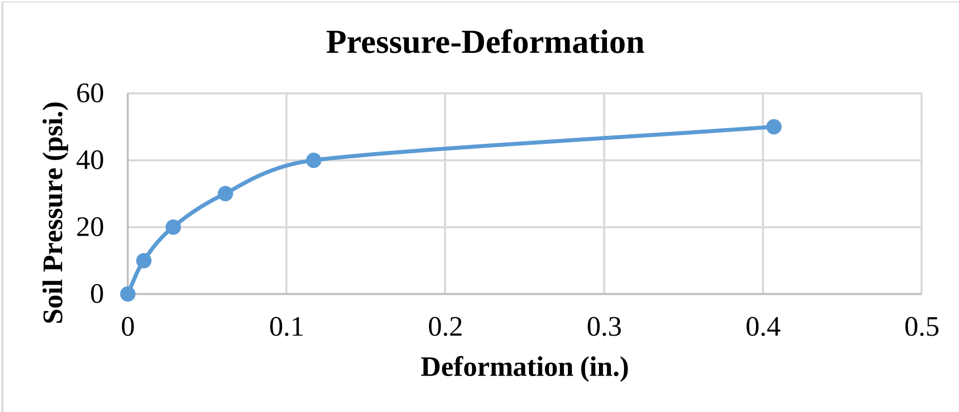


Figure 39: Pressure vs. Corner Deformation of Panel with 10 Inch Space between the Concrete Layers

The figures above present the FE analysis of the various 3D welded wire panels described in this section. Continuing with the previously presented trend of a rapid increase in the soil pressure resulting in a slow increase in the deformation. However after a certain point the panel deformation increased in more significant fashion compared to the pressure.

Panel Spacing Comparison

Considering the various panels a comparison can be made about their behavior and performance using their respective pressure vs. deformation curve. A better understanding of how the spacing between the concrete layers affected the results can be reached.

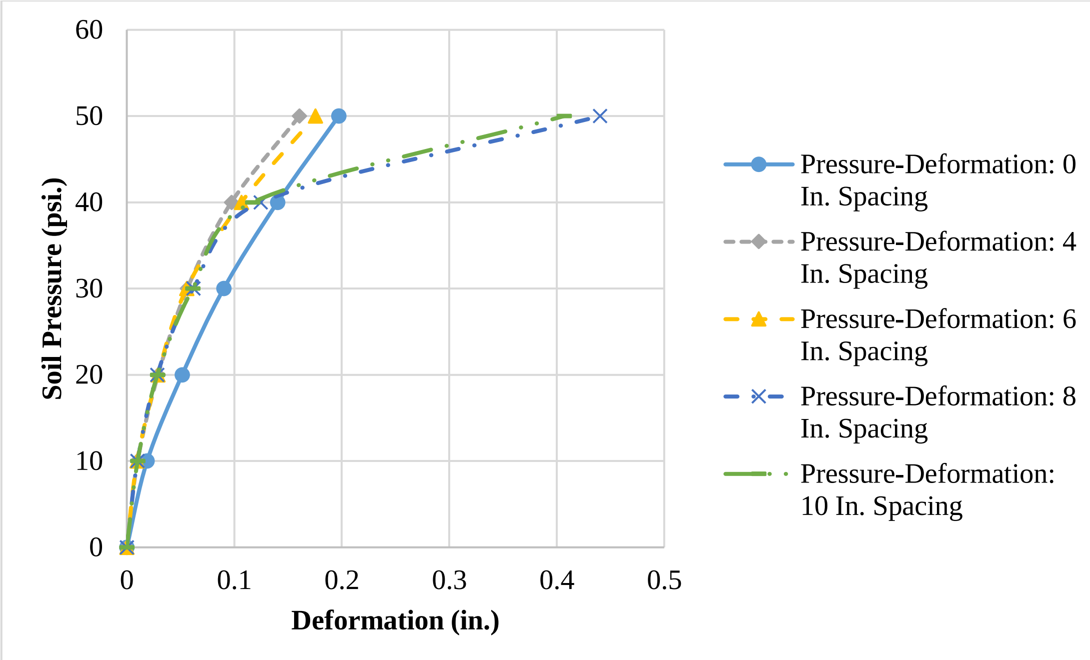


Figure 40: Pressure vs. Corner Deformation of Panels with Varying Distance of Space between the Concrete Layers

In Figure 40, the comparison of the results for the FE analysis is displayed. The panels with the 0, 2, 4, 6, 8, 10 inch space between the concrete layers all highlighted similar behavior. Relatively speaking under the same soil pressure, the deformations were nearly identical. Through observations that were made the panel that featured no spacing between the concrete layer was the weakest for the majority of the analyzes. Also, note that when the panels with the 8 and 10 inch spacing yielded their deformation increased at a significantly quicker rate than the others. The effects of the soil pressure on the steel components of the wire panel is the driving force of the yielding of the panel. The steel diagonals in these cases play a more essential role in the panel's behavior therefore, when the diagonals yield the deformation in the overall panel is greatly affected.

Panels with Varying EPS Thickness

In addition to the models of 3D welded wire panels with different spacings between the concrete layers there are models that were created using different EPS thicknesses in between the concrete layers. Similar to the previous cases a FE analysis were conducted on these additional models. In these models the thicknesses of the EPS block to be employed are 4 inches, 6 inches, and 8 inches.

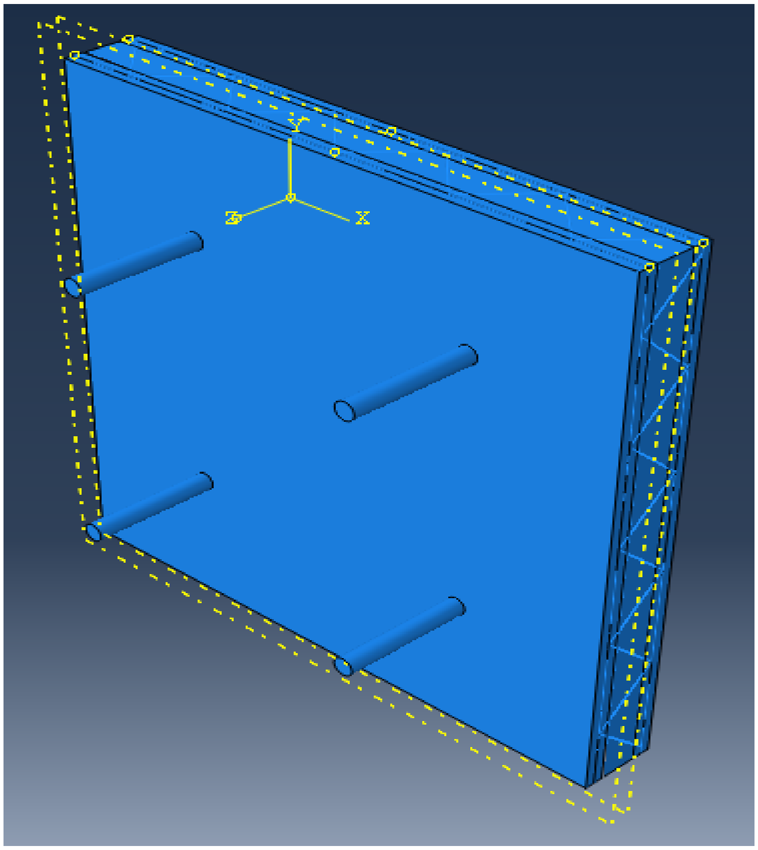


Figure 41: 3D Welded Wire Panel with 4 Inch EPS Thickness

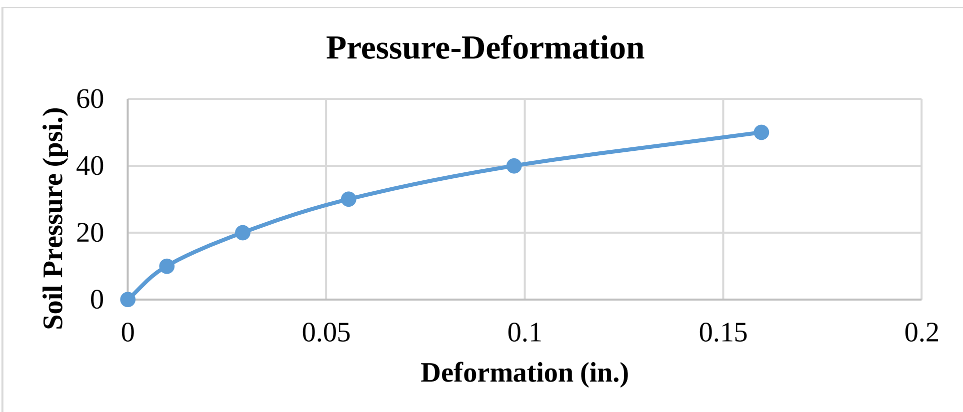


Figure 42: Pressure vs. Corner Deformation of Panel with 4 Inch EPS Thickness

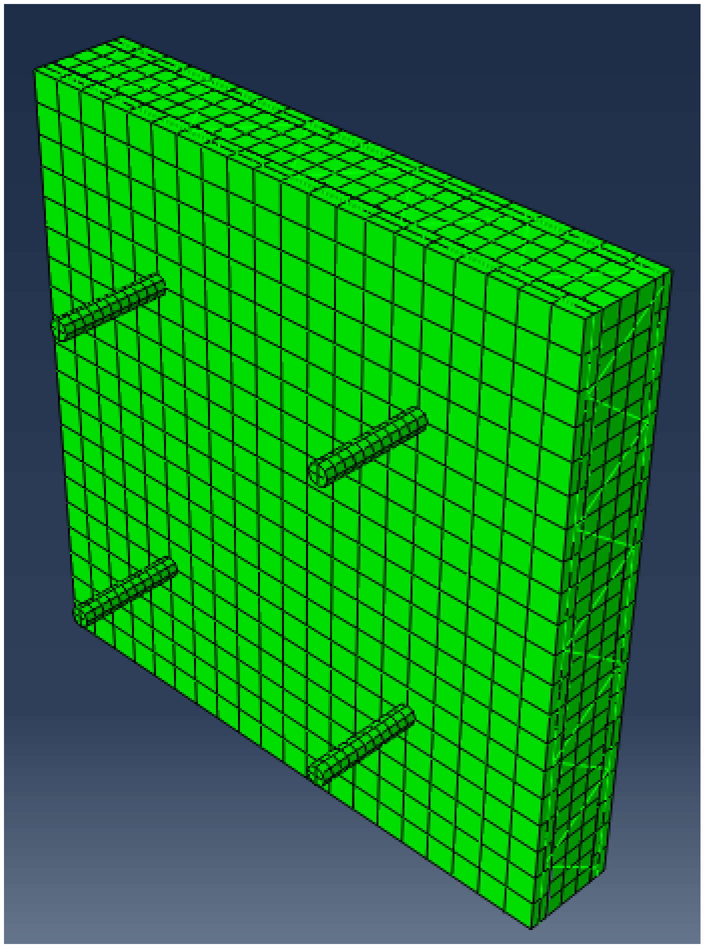


Figure 43: 3D Welded Wire Panel with 6 Inch EPS Thickness

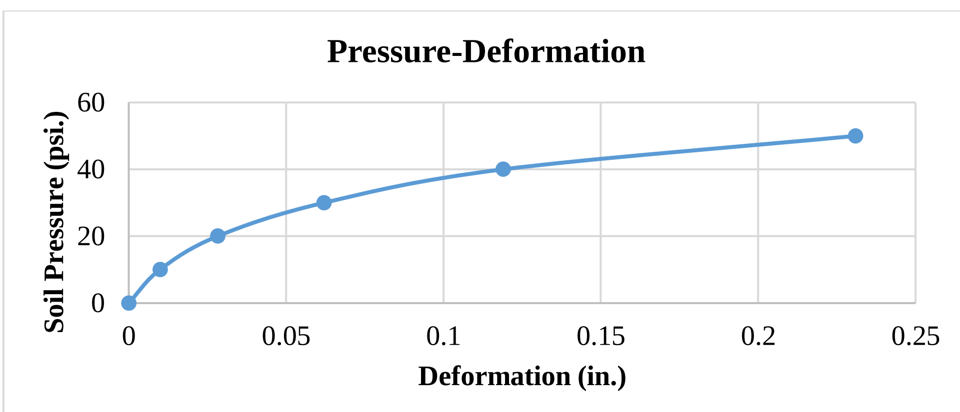


Figure 44: Pressure vs. Corner Deformation of Panel with 6 Inch EPS Thickness

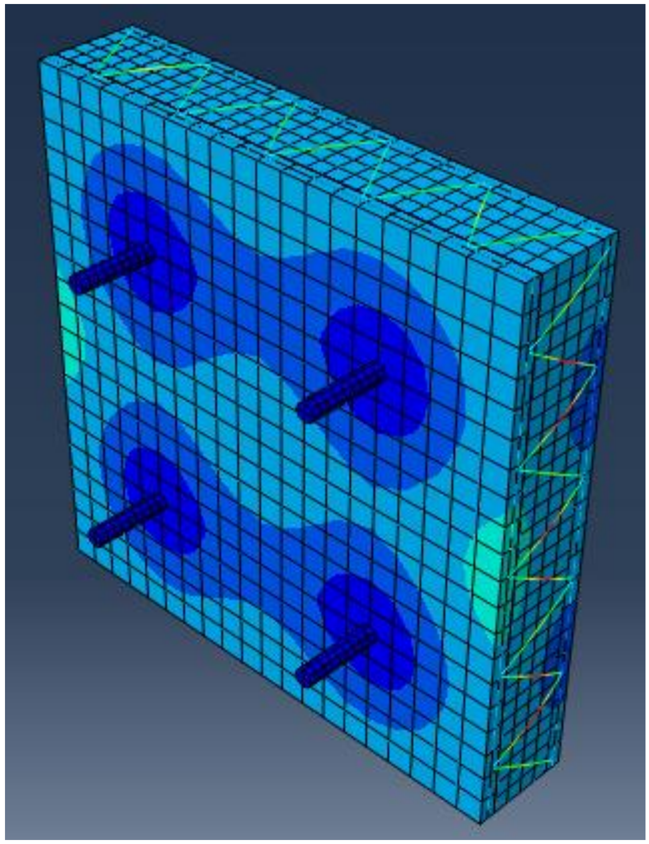


Figure 45: 3D Welded Wire Panel with 8 Inch EPS Thickness

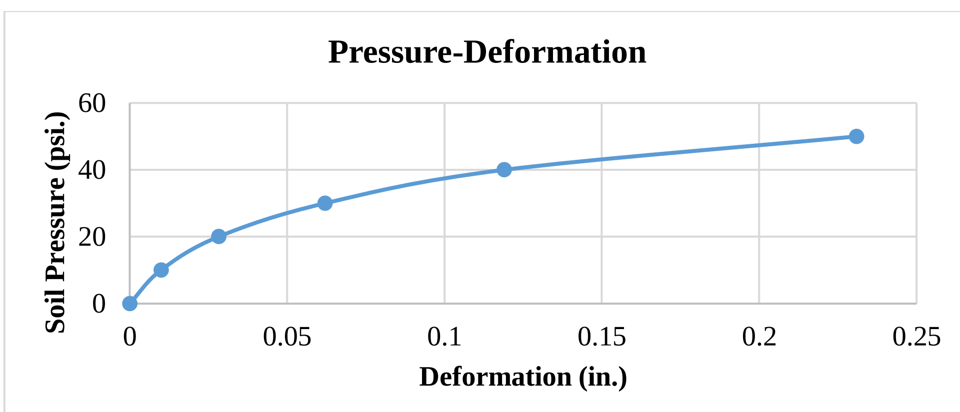


Figure 46: Pressure vs. Corner Deformation of Panel with 8 Inch EPS Thickness

Varying EPS Thickness Comparisons

Using the results obtained through the FE analysis of the three previous models comparisons can be made and used for this work. Comparing the results can create a better understanding of how the EPS thickness affects how the 3D welded wire panel behaves under soil pressure.

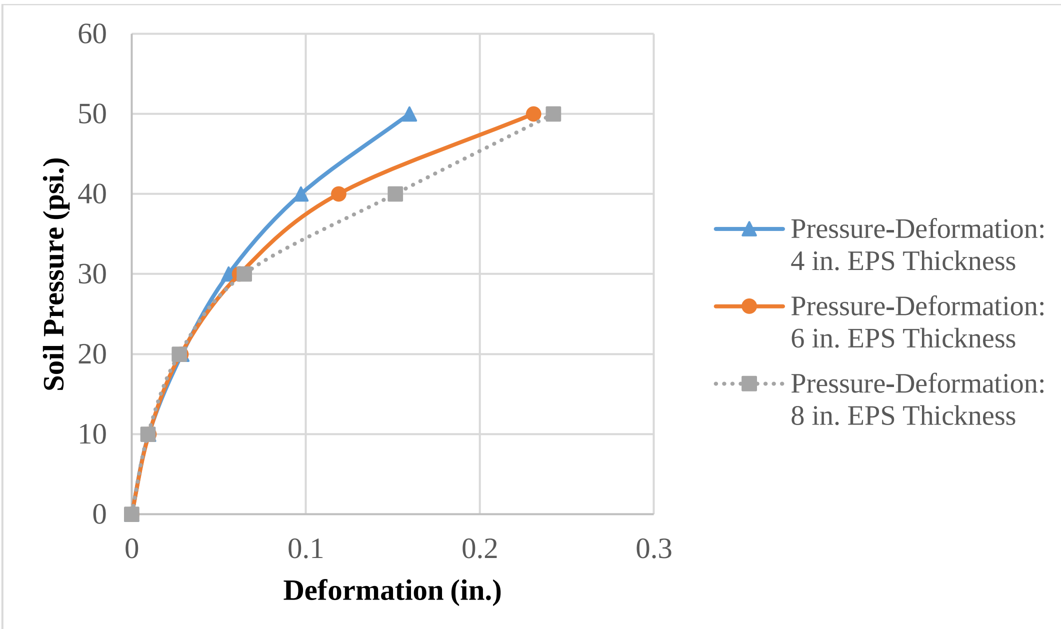


Figure 47: Pressure vs. Corner Deformation of Panels with Varying EPS Thicknesses

The above figure showcases the pressure-deformation curve of all three models mentioned in this section. It should be noted that in order to include varying EPS thicknesses the spacing between the concrete layers have to be changed simultaneously. Therefore, that aspect of these panels do play a role in the panel behavior. With that being noted the three panels are very similar, especially the panels with the 6-inch and 8-inch thick EPS. The 4-inch thick EPS panel does seem to be a little stronger. Perhaps due to the fact that the EPS block is more condensed making it stronger.

CHAPTER 5

FINDINGS AND RECOMMENDATIONS

MSE walls should be capable of increased soil stability, the ability of long-term performance, protection from erosion, and display the suitability to have both permanent and temporary applications (Armtec 2016). Therefore, an option that can be used for the facing of a MSE wall facing is the 3D welded wire panel. Numerous finite element analyses were conducted and the presented in the last chapter. The generation of these results are essential for this thesis in order to obtain a better understanding of the behavior of the 3D welded wire panels. Note that the findings and information for which panels had the better performance are specific to the conditions and specifications detailed throughout this thesis. In other words the conclusions drawn are specific to the material properties, boundary conditions, loads, and other parameters mentioned previously.

Panel Dimensions

When examining the comparison of how the 4x4 ft. panel and 5x5 ft. panel performed the 4x4 ft. panel had an advantage. For the conditions described in this work the panel with the smaller area had less deformation at the same soil pressure as the larger counterpart. Due to this outcome, factors such as the size of the concrete layers, steel mesh, and EPS layer need to be added to the numerous considerations that need to be made when designing 3D welded wire panels and selecting the overall panel dimensions. Recall that for the square panels examined the dimensions in terms of length and width of the concrete layers, steel mesh, and EPS layer are all equal.

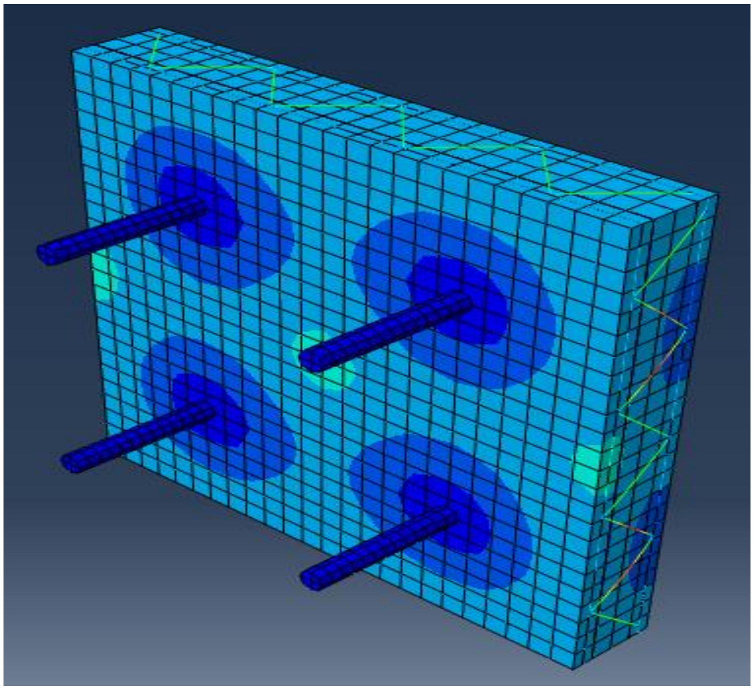


Figure 48: 4x4 ft. Panel showing the Deformation Contour

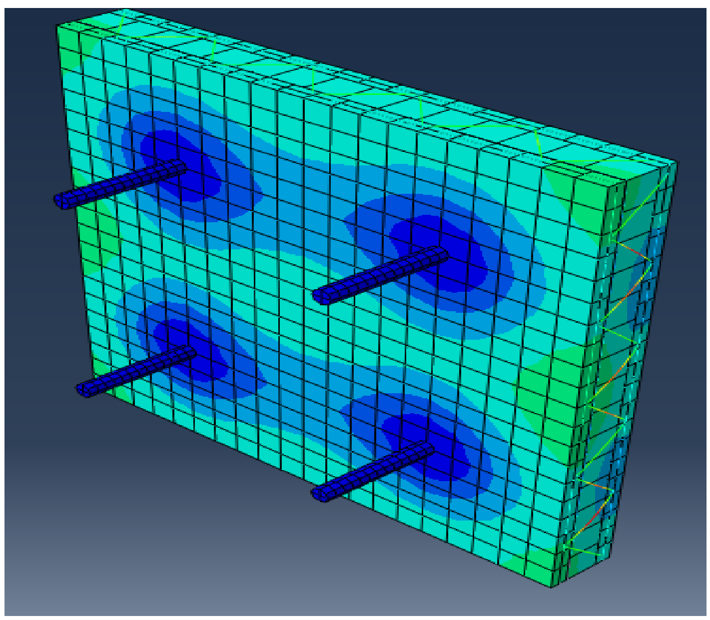


Figure 49: 5x5 ft. Panel showing the Deformation Contour

The above figures present both the 4x4 ft. panel and 5x5 ft. panel. Note that the figures used specifically show the deformation contours of each panel as they are presented in Abaqus. In Abaqus the deformation can be plotted through contours in which the colors displayed can offer a better visualization of deformation. The scale in color ranges from blue to red, with red representing the maximum deformation in view. From the figures it can be observed that the 5x5 ft. panel is deforming more than the 4x4 ft. panel. When selecting a panel to implement as a MSE wall facing based on the thesis results it is suggested that the 4x4 ft. panel is preferable in terms of strength compared to a 5x5 ft. panel. In this thesis the strength of a panel can be determined from how increasing the soil pressure affected the increase in corner deformation.

Panel Spacing

In regards to what the spacing should be between the concrete layers, this study suggests that a 4 inch spacing creates a strong panel for the rebars, steel wire mesh, and diagonal members. Compared to the other panels with 0, 6, 8, and 10 inches of space between the concrete layers the panel with 4 inches of space showcased the most strength. It was observed that the steel diagonals in these cases play an important role in the panel's behavior therefore, when the diagonals yield the deformation in the overall panel is affected.

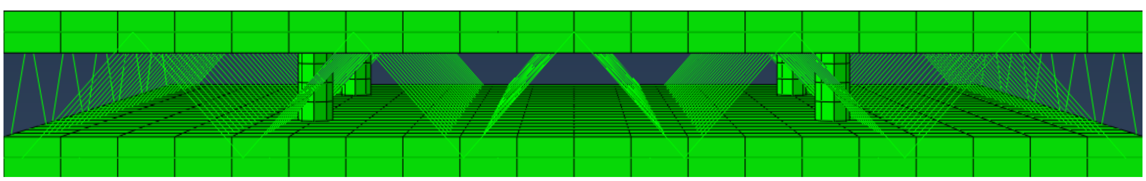


Figure 50: Space between the Concrete Layers on the 3D Panel

The above figure shows the space between the two concrete layers and how the steel diagonals are placed all throughout the 3D panel. The yielding in the steel diagonals begin to occur when the yield stress of the steel is approached. In the case of this work that stress was specified as 50,000 psi. In failure, the steel diagonals yield or buckle and the panel loses strength. Notice that as the space between the concrete layers increases the length of the steel diagonals also increase and the buckling happens in more diagonal members. Changing the space between the concrete layers directly affect how the steel diagonals on the panel perform. The truss-like behavior of the steel in the panel is extremely important to the 3D panel. The truss behavior assists with the rigidity and shear elements for full composite behavior. A 3D wall panel receives its strength and rigidity from the diagonal cross wires welded to the welded wire mesh on each side of the panel (Kabir 2005). The figures below give a visual representation of how the steel diagonals look before the soil pressure is applied on the 3D panel as well as how the steel diagonal appear as yielding begins to occur in the 3D panel.

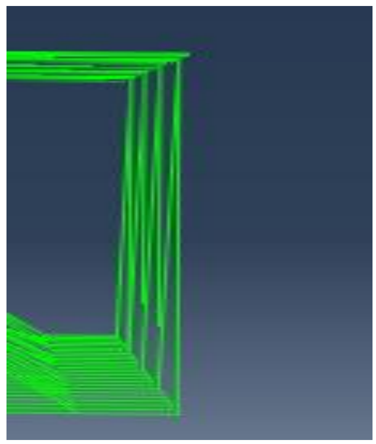


Figure 51: Undeformed Shape Steel Diagonals on the Side of the 3D Panel

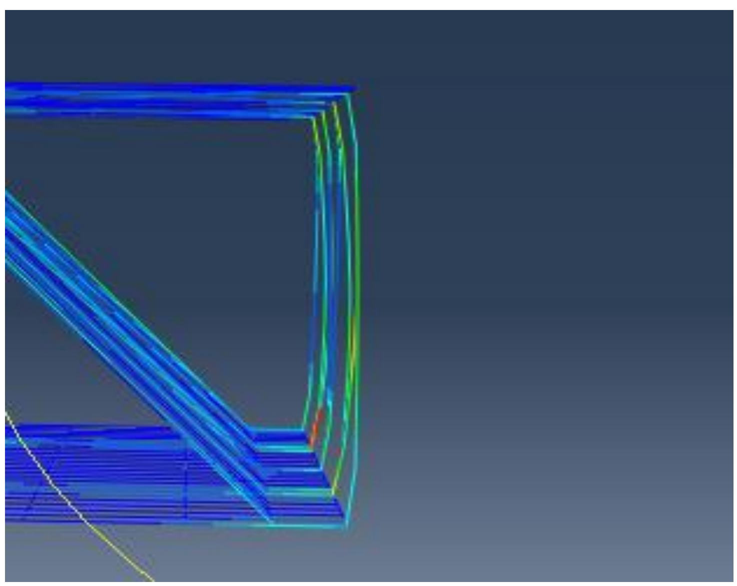


Figure 52: Deformed Shape Steel Diagonals on the Side of the 3D Panel

It should be noted that all of the panels with space between the concrete layers were stiffer than the panel with no space between the layers where the two concrete layers were touching because of an increase in moment of inertia of the section. One recommendation that can be made based on the results is that large distances between the concrete layers should not be considered as the buckling of diagonals can reduce the performance of panels. Initially the panels that had 8 and 10 inches of space between the concrete layers were stiffer however, after a certain soil pressure was applied on the panel the corner deformation in respect to the anchors in those panels drastically increased.

EPS

Fundamentally the thickness of the EPS layer is equal to the distance between concrete layers. Typically when EPS is included in the design of a 3D welded wire panel it is sandwiched between the concrete layers leaving no space between the EPS and concrete. Note that in the both cases where there either was EPS or no EPS the panel performed identical when there was 4 inches of space between the concrete layers and also for other thicknesses.

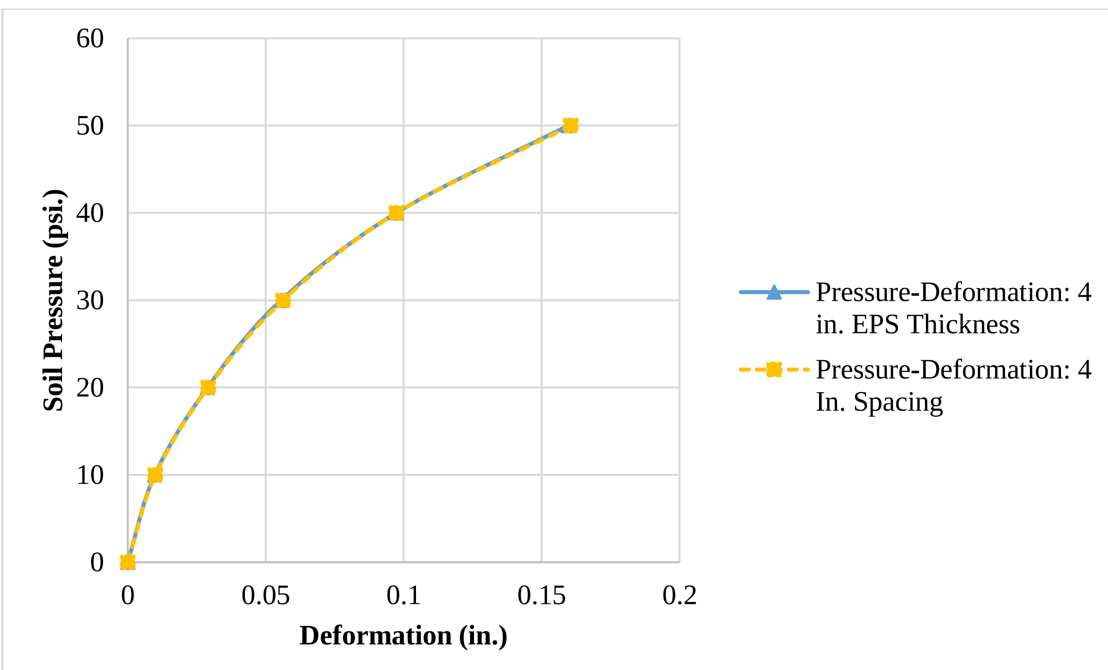


Figure 53: Soil Pressure vs. Deformation Comparison of 4x4 ft. Panel with and without EPS

Figure 53 presents the panel with and without EPS to compare the effects of EPS. The panel with 4-inch space between the concrete layers with and without EPS are analyzed. It is observed that the presence of EPS does not play much of a role in the performance of the panel. The results of the FEA on the 4x4 ft. panel with and without EPS are so similar that the curves displayed are practically identical. Although the EPS layer is not the driving factor in how a 3D panel behaves under soil pressure it is an important to have in the 3D panel. The EPS is a good insulator for the panel, it provides uniformity to the panel when shotcrete is applied during construction, and it increases the moment of inertia of the section as much as required in design.

Suggested Panel

When determining the design of the ideal 3D welded wire panel design for a MSE wall facing several considerations have to be made. Considerations should include geologic conditions, topographic conditions, environmental conditions, size of the structure, nature of the structure, aesthetics, durability considerations, performance criteria, availability of materials, experience with a particular system or application, and cost (Ryan R. Berg & Barry R. Christopher, 2009). However for the identical conditions and parameters in this study the type of 3D panel that will perform best and is suggested for use is a 4x4 ft. panel with 4 inches of space between the concrete layers filled with a 4 inch thick EPS layer.

CHAPTER 6

CONCLUSION

Summary

A literature review was conducted in an effort to establish a background on MSE walls and 3D welded wire panels. In order to evaluate the behavior and performance a finite element modeling of Mechanically Stabilized Earth (MSE) walls using welded wire wall panels was performed in Abaqus. The results of the finite analysis for several models were gathered, presented, and compared.

The objective of this thesis was to determine whether the implementation of 3D wire panels as a viable alternative for MSE wall facing was possible. It was observed that the use of 3D welded wire panels as the facings of Mechanically Stabilized Earth (MSE) Walls is possible. Due to reduction of the weight of the MSE wall facing because of the use of 3D welded wire there will be substantial savings in the construction, equipment, labor, material, and transportation costs as well as maintaining the stability and performance.

Chapter 1 described the objectives, scope, and thesis outline. While Chapter 2 provided a brief summary of previous research works related to MSE walls and 3D welded wire panels through literature review. Chapter 3 showcased the development of the FE model for the actual 3D welded wire panel. Additionally a means of verification for finite element analysis was detailed Chapter 3. The results of the pullout tests are presented and discussed in Chapter 4. The results were represented through a serious figures that included data on soil pressure, maximum stress and deformation. Results generated for each model were discussed and comparison so that conclusions from the research can be drawn. Chapter 5 explains the findings from the results and presents suggestions for the panels in conditions specific to this thesis.

Conclusions

Based on the information that has been presented in the previous chapters, the following conclusions can be made:

- The finite element method was an appropriate tool for the analysis of the 3D welded wire panel.
- Changing design parameters of the panel does affect behavior of the 3D welded wire panel.
- Effects of changing the area of the panel can be observed through the comparison of the 4x4 ft. panel and the 5x5 ft. panel. The 4x4 ft. panel can be described as "stiffer."
- The behavior of the proposed 5x5 ft. 3D welded wire panel versus a typical solid concrete facing can be observed. Based on the presented results the welded wire panel can be used as MSE walls.
- The use of a thicker EPS did not improve performance of the 3D wire welded panel.
- In fact in this work the 4 inch thick EPS was observed to have better performance.
- These results can only be implemented to 3D welded wire panels as MSE walls facings, \for the panels and materials that were examined in the present study.

Recommendations

The present study, helped create a better understanding of Mechanically Stabilized Earth wall facings and 3D welded wire panels. Additionally the research done in this work did contribute more knowledge in the FE modeling of panels as well as effects of variations in these models. However, further investigations can be recommended:

- Experimental bending and pullout tests on anchorage systems and panels
- Additional numerical analysis of varying models with changes in inputs for panel dimensions, rebar sizes, rebar distances, material properties, , types of elements, mesh sizes, etc. can be performed for the optimization of 3D welded wire panels.

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